JOURNAL OF APPLIED PHYSICS

JUNE
1940
Vol. 11 No. 6

Special Issue on Measurement and Control of Temperature

JOURNAL OF APPLIED
PHYSICS

JUNE, 1940 Vol. 11, No. 6

In This Issue

Page

Temperature Scale, a Proposed Change in Definition F. G. BRICKWEDDE 371

Temperature and Temperature Scales H. T. WENSEL 373

Thermoelectric Thermometry WM. F. ROESER 388

Optical Pyrometry W. E. FORSYTHE 408

Temperature Radiation Emissivities and Emittances A. G. WORTHING 421

Mechanism of Spark Discharge in Air at Atmospheric Pressure. I LEONARD B. LOEB AND JOHN M. MEEK 438

Conference on Applied Nuclear Physics 448

Directory of Temperature-Measuring and Control Instruments iv

In Every Issue

Here and There 420, 437, 447, 449

Contributors to This Issue 450

Index to Advertisers xx

BOARD OF EDITORS

ELMER HUTCHISSON, *Editor*

Associate Editors

F. BITTER
W. E. FORSYTHE
L. A. JONES
B. E. WARREN
J. B. WHITEHEAD

Publication of the American Institute of Physics

ADMINISTRATIVE STAFF

HENRY A. BARTON, *Director*

MADELINE M. MITCHELL, *Publications Manager*

JOHN T. TATE, *Adviser on Publications*

GOVERNING BOARD

PAUL E. KLOPSTEG, *Chairman*
GEORGE B. PEGRAM, *Secretary*
KARL T. COMPTON
WHEELER P. DAVEY
FLOYD A. FIRESTONE
HARVEY FLETCHER
R. C. GIBBS
ARTHUR C. HARDY
GEORGE R. HARRISON
A. STUART HUNTER
H. R. LILLIE
FREDERIC PALMER, JR.
GEORGE B. PEGRAM
W. B. RAYTON
JOHN T. TATE
WALLACE WATERFALL

THE JOURNAL OF APPLIED PHYSICS, published monthly at Prince and Lemon Sts., Lancaster, Pa., is devoted to physics in its role as the science basic to other natural sciences and to the arts and industries. Previous to 1937 this publication was known as PHYSICS. It aims to be of service not only in physical laboratories, but also in the laboratories of industrial, chemical, geological, geophysical, meteorological, radio, and similar concerns. THE JOURNAL OF APPLIED PHYSICS publishes editorials, news of physicists and reviews, as well as technical papers of applied physics.

Manuscripts should be submitted to Elmer Hutchisson, Editor, University of Pittsburgh, Pittsburgh, Pennsylvania.

SUBSCRIPTION PRICE

	U. S., POSS. AND CANADA	FOREIGN
To members of scientific societies	$5.00	$5.70
To all others	7.00	7.70

Single copies are $.70 each.

Changes of address and proofs should be addressed to the Publications Manager.

Subscriptions and orders for back numbers should be addressed to Prince and Lemon Streets, Lancaster, Pa. or to the American Institute of Physics, 175 Fifth Avenue, New York, N. Y.

Advertising rates supplied on request. Orders, advertising copy and cuts should be sent to the American Institute of Physics.

Entered as second class matter at the Post Office at Lancaster, Pennsylvania, under the Act of March 3, 1897.
Accepted for mailing at the special rate of postage provided for in the Act of February 28, 1925, authorized May 2, 1932.

Copyright 1940, by the American Institute of Physics.

THIS CONSTANT TEMPERATURE BATH
Controls to 1/1000 of a Degree

When highly accurate laboratory measurements must be made under precise temperature conditions, this Constant Temperature bath—and apparatus immersed in it—can be automatically maintained at a temperature which is constant within 0.001 C. Or, if the user manually adjusts heat input to the bath whenever large changes in room temperature occur, the bath can be held within 0.0005 C. Uniformity is such that no point in the work space differs from any other by more than 0.0005 C.

Bath temperature can easily be raised or lowered, in steps of approximately 0.001 C, simply by moving a few plugs in a resistance box. Range of control is from 0 to 60 C. For low-temperature operation, the bath contains a built-in cooling coil through which an external cooling medium can be circulated.

EMBODIES A HIGH-SENSITIVITY WHEATSTONE BRIDGE

Changes in bath temperature are detected by a special resistance thermometer mounted in the bath and connected to a built-in Wheatstone bridge of high sensitivity. When temperature changes, the bridge galvanometer reflects a beam of light to a photo-cell, which, in turn, operates a Thyratron control system to regulate input to the electrical heating units in the bath.

To hold every part of the equipment placed in this bath at the same uniform temperature, an extra-large, motor-driven stirrer circulates oil continuously throughout the bath. Circulation follows a definite path . . . oil is forced up at the center and flows over the top of an inner container which incloses the actual work space.

STURDY, COMPACT EQUIPMENT

Built as a unit, bridge and bath are mounted in a well-finished oak cabinet. On top of the cabinet, within easy reach, is the plug-type resistance box which forms one arm of the bridge and is used to set the bath temperature.

Galvanometer, photo-cell and Thyratron are inclosed in a separate steel box for wall mounting.

Ample work space is provided—16 x 16 inches, and extending 9 inches below the surface of the oil. Oil capacity is 31 gallons.

Alternating current is used, except for the control bridge which operates from dry cells. So that the bath can be easily moved to any part of the laboratory, it is equipped with substantial rubber-tired rollers.

4958-A1 PRECISE CONSTANT-TEMPERATURE BATH ASSEMBLY . . $1490.00

LEEDS & NORTHRUP COMPANY, 4978 STENTON AVE., PHILA., PA.

LEEDS & NORTHRUP

MEASURING INSTRUMENTS • TELEMETERS • AUTOMATIC CONTROLS • HEAT-TREATING FURNACES

For conductivity measurements of the highest precision, this constant-temperature bath provides the necessary uniformity and constancy.

NEW WILEY BOOKS

Spring-Summer 1940

FOUNDATIONS OF MODERN PHYSICS

By **T. B. BROWN,** *Professor of Physics, The George Washington University.*

This textbook stresses the close relationship between the new physics and the old. The experimental viewpoint of modern physics is maintained, and the discussion serves to show how these experiments bear out the theories which have been advanced. The book is characterized by a non-technical style, a logical order of presentation, and the use of simple mathematics.

Approximately 314 pages 144 illustrations 6 by 9 Probable price, $3.00

COLLEGE PHYSICS

By **JOHN A. ELDRIDGE,** *Professor of Physics, State University of Iowa.*

A revised edition of this successful textbook is now in press. The approach remains the same—that of an elementary textbook with a special appeal both to physics majors and to those taking the course for purely cultural purposes. The second edition will include an increased number of problems, the expansion of certain sections with a view to clarification of the discussion, and the addition of new data.

Second Edition Approx. 674 pages 450 illus. 5½ by 8½ Probable price, $3.75

GENERAL PHYSICS FOR STUDENTS OF SCIENCE

By **ROBERT BRUCE LINDSAY,** *Hazard Professor of Physics, Brown University.*

This textbook is intended for an introductory course in college physics, for sophomore students of science who have had mathematics through elementary calculus, or as an intermediate and more thorough treatment, for a course for students who have already had an elementary non-mathematical course in physics.

534 pages 265 illustrations 6 by 9 $3.75

PROCEEDINGS OF THE SEVENTH SUMMER CONFERENCE (1939) ON SPECTROSCOPY AND ITS APPLICATIONS

Edited by **GEORGE R. HARRISON,** *Professor of Physics, Massachusetts Institute of Technology.*

The twenty-nine papers of the 1939 Conference, presenting latest developments in the applications of the rapidly-growing science of spectroscopy. The subjects covered include general background and methods, specific types of analysis, recently developed apparatus, absorption spectrophotometry, etc.

154 pages 69 illustrations 7½ by 10 $2.75

TELEVISION—THE ELECTRONICS OF IMAGE TRANSMISSION

By **V. K. ZWORYKIN** and **G. A. MORTON,** *both with the RCA Manufacturing Company.*

A detailed survey of this newest of practical means of communication. The book is written from an engineering standpoint. Emphasis is placed on application of the fundamental principles. The authors are two of the foremost men in the field.

646 pages 494 illustrations 6 by 9 $6.00

JOHN WILEY & SONS, INC., 440-4TH AVE., NEW YORK

HARVARD COLLEGE
JUN 25 1940
LIBRARY

Journal of Applied Physics

Volume 11 June, 1940 Number 6

The Temperature Scale, a Proposed Change in Definition

ONE of the aims of precision thermometry is the improvement of the accuracy with which information regarding temperatures may be conveyed without transporting the thermometers used in the temperature measurements. Precision thermometers are necessary for the accurate measurement of temperatures, but as for other measurements a precisely defined and exactly reproducible scale is necessary for conveying definite information regarding the results of measurements obtainable with precision instruments. Paralleling the development of the thermometer for precision measurements there is an interesting development of the definition of the temperature scale.

The first thermometer—really a thermobaroscope, invented probably by Galileo about 1595—had an arbitrary, undefined scale. The hermetically sealed *spirit* thermometers for which the Florentine Academy of Sciences (1657–1667) was famous were among the earliest thermometers graduated and numbered in accordance with a rule. These thermometers were used for a long time in many places in Europe for meteorological measurements and investigations of thermal phenomena. The 17th century method of defining the temperature scale, embodied in the procedure of the time for graduating and numbering thermometers, is different from our present method of defining the scale. An arbitrarily chosen number was assigned to the temperature of some *one* thermal state as for example that of melting snow or ice or that of a cave or deep cellar, and the position of the liquid meniscus of the thermometer at this temperature was marked on the stem. The definition of the scale was completed by making equal temperature intervals correspond to expansions or contractions of the thermometer fluid by the same fraction of that volume occupied by the fluid at the temperature of the basic point.

At the beginning of the 18th century, considerable interest was shown in the improvement of temperature determinations. This led to important improvements in thermometers and in the definition of the temperature scale. Fahrenheit was the outstanding figure of this period of development. He was largely responsible for the introduction of the mercury thermometer and the present method of defining the temperature scale based on the use of two *fixed* points. The 17th century method of calibrating liquid-in-glass thermometers based on the use of a single calibration point was not capable of the accuracy attainable using two calibration points because the thermometer fluids differed in composition and expansivity, and no allowance was made for differences in expansivities of different thermometer glasses.

The temperature scales of the 17th and 18th centuries depended upon the thermometric fluids used. Consequently, quantitative statements of natural laws in which temperatures entered involved arbitrarily chosen thermometric fluids. A desire manifested itself in the 19th century to express these laws without reference to the thermometric fluid. In 1848, William Thomson, later Lord Kelvin, showed that the fundamental principles of thermodynamics may be used to define temperature scales that are independent of the thermometric substance, and in 1854 Joule and Thomson published the definition of the thermo-

dynamic scale that is today the basis of nearly all temperature measurements. This thermodynamic scale is established with gas thermometers in thermometer laboratories for the calibration of more convenient, practical thermometers to serve as secondary standards of thermometry, and for the determination of such practical scales as the International Temperature Scale.

The product pV of an ideal gas is proportional to the absolute thermodynamic temperature defined by Joule and Thomson. Accordingly, *ratios* of thermodynamic temperatures are related to the pressures and volumes of constant volume and constant pressure, ideal gas thermometers by the equation

$$\frac{T_1}{T_2}=\left(\frac{p_1}{p_2}\right)_{V\ \text{const}}=\left(\frac{V_1}{V_2}\right)_{p\ \text{const}}. \qquad (1)$$

Real gases deviate from the laws of ideal gases, but corrections can be made so that *ratios* of thermodynamic temperatures can be determined with real gases.

Equation (1) is not a complete definition of a temperature scale, since it does not yield a number for the temperature of any thermal state. The definition may be completed by assigning an arbitrarily chosen number to either (1) the temperature of some one reproducible thermal state, or (2) the difference between the temperatures of two states. The latter method conforms to the definitions of the Fahrenheit and centigrade scales. In 1854 Joule and Thomson discussed both methods of fixing the scale. They proposed the use of the latter method then in order to retain a connection with the Fahrenheit and centigrade scale, but they wrote that "the former is far preferable in the abstract and must be adopted ultimately." They stated that when the temperature of the ice point, T_i, on the absolute centigrade or Kelvin scale is known sufficiently accurately (the present *best* value is 273.16° with a probable error of ±0.01°) it may be desirable to change to method (1), assigning to the ice point the best value of T_i on the present absolute centigrade scale. Thus continuity can be maintained with the centigrade and Fahrenheit scales now in use and thermometric data existing at the time of the change would be unaffected. Thus the change would cause little or no inconvenience.

If the change in definition proposed by Joule and Thomson is adopted the numerical value of the temperature T_i of the ice point on the absolute scale will be fixed exactly by the definition of the scale, the steam point will be reduced to the status, for thermometry, of other boiling points, and it will become an object of experimental research to determine by what small fraction of a degree the interval between the ice and steam points departs from 100°. If the change were made now the probable error in the ice-steam interval on the new scale would be ±0.003°. Some important advantages are to be gained by the proposed change: (1), the factor $T_i=T-t$ for converting absolute temperatures to temperatures on the scale with 0° at the ice point would be fixed precisely by the definition of the temperature scale; (2) thermodynamic temperatures would be measurable with somewhat greater accuracy and more simply since the measurements at the steam point, now required for the determination of the present temperature scales but not for the proposed scale, contribute to present experimental errors and difficulties; and (3) there would be no necessity as there is at present for revising previously determined temperatures of fixed points whenever new determinations are made of the fundamental pressure and volume coefficients between the ice and steam points of thermometric gases. As a result of the changes made in previously determined temperatures to take advantage of new determinations of the fundamental coefficients of thermometric gases, and the interconversions of temperatures on the Celsius and Kelvin scales, involving conversion constants ranging at present from 273.10° to 273.19°, uncertainties have crept into the temperatures of fixed points that were not inherent in the original measurements of these temperatures. Such difficulties would be avoided with the adoption of the proposed change.

Recently W. F. Giauque directed attention to the change recommended by Joule and Thomson and proposed that steps be taken to bring about its adoption.

F. G. BRICKWEDDE
National Bureau of Standards,
Washington, D. C.

Temperature and Temperature Scales*

H. T. WENSEL

Chief of Pyrometry Section, National Bureau of Standards, Washington, D. C.

An attempt has been made here to cover the general subject of temperature and methods of expressing temperature. The fundamental concepts involved are developed, the basis and significance of a thermodynamic scale are discussed, and the relation of various practical scales, in particular the International Temperature Scale, to the thermodynamic scale is explained.

1. Heat and Temperature

OUR fundamental concept of temperature is obtained from the sensation of warmth or cold which we experience upon touching any object. Such expressions as "ice-cold," "cool," "tepid," "lukewarm," "warm," "hot," "sizzling," "red-hot," etc. indicate that our qualitative appreciation of temperature precedes our use of numerics to characterize it. Our experience further tells us that when two similar bodies at different temperatures are placed in thermal communication (and cut off from such communication with all other bodies) the hot body becomes colder and the cold body becomes hotter until the two reach a thermal state of temperature which, judged by our senses, is the same.

On the other hand, our concept of what takes place during this equalization of temperature is obtained only after considerable inductive reasoning to generalize a great mass of quantitative data.

It was in the 1790's that the American physicist, Benjamin Thompson (Count Rumford) made his quantitative measurements of heat while boring the King of Bavaria's cannon. However, the generalization of our concept of heat, which we find in Helmholz' paper on the conservation of energy, did not appear until 1847. Our concept of heat, as an exact physical term, is defined as "energy that is transferred from one body to another by a thermal process," where, by a thermal process, is meant radiation, conduction, and/or convection.

Our observation then, plus our concept of heat exchange as an energy transfer, enables us to say that in the equalization of temperature, heat passes from the hotter to the colder body. In seeking for a definition of temperature, therefore, we find it difficult to improve on the one given by Maxwell, which is that "The temperature of a body is its thermal state considered with reference to its ability to communicate heat to other bodies."

Of two bodies having different temperatures, the one which communicates heat to the other is said to be at the higher temperature and in devising temperature scales (i.e., in assigning numbers to definite thermal states) its temperature is customarily, though not necessarily, assigned the greater number. In that connection it may be of interest to mention the fact that the first scale which divided the interval from the freezing point to the boiling point of water into 100 degrees (i.e., the first centigrade scale) was one devised by Celsius on which the freezing point of water was numbered 100 and the boiling point 0.

Suppose we have a body A which can communicate heat to a body B, i.e., A is at a higher temperature than B. Experience shows that if a third body, a thermometer, is placed in intimate thermal contact with B (the colder) and allowed to remain there until all heat transfer between them has ceased, the thermometer, when now placed in contact with A will, *in general*, receive heat from the latter. Conversely, if the quantity

* The treatment presented here is very similar in parts to that given in the article on "Temperature" by Joseph S. Ames in the Pyrometry Symposium of 1919 published by the A.I.M.M.E. In addition, the author has made use of lecture notes supplied by Professor Ames to his students during the early 1920's. This paper was presented at the Symposium on Temperature, Its Measurement and Control in Science and Industry, November 2–4, 1939, New York, New York.

of heat which a body A can communicate to a particular thermometer is greater than that which B can communicate to that same thermometer, then A will *in general* be able to communicate heat to B. When this is not the case certain difficulties must be faced.

If a piece of platinum is placed in the stream of illuminating gas from an unlighted Bunsen burner, the platinum will get hot even though it and the gas were initially at the same temperature. The platinum will catalyze the combination of the gas with oxygen even at room temperatures. In fact gas lighters have been made using this principle. The transfer of energy from the cold gas to the platinum is not a simple thermal process but involves a different kind of process, a chemical reaction. A bare platinum thermocouple or a bare platinum resistance thermometer, therefore, cannot indicate the temperature of a gas or of a flame. Questions of how we measure temperatures in a flame, in an electric discharge, etc., were discussed by other contributors to the Temperature Symposium. The present discussion is limited to cases in which the bodies to which temperature numbers are to be assigned are free of all electrical and chemical changes and in which the introduction of the temperature measuring device does not give rise to such changes.

II. Temperature Scales

The process of assigning numbers to temperatures is analogous to the process of naming streets and numbering houses so that the location of any particular building may be unambiguously specified. Since the number of buildings in any city is finite, we are not restricted to numbers for designating buildings. Such designations as the "Flatiron Building," "Madison Square Garden," and the "Cotton Club" are perfectly definite. A similar scheme will serve for some but not for all temperatures. There are a number of thermal states or temperatures which may be recognized and uniquely characterized by definite phenomena which take place at these temperatures. The most important of these temperatures (so-called "fixed points") are the melting and boiling points of pure substances at a specified pressure. But inasmuch as there is an infinity of thermal states or temperatures between these fixed points, the first requirement for the general measurement and specification of temperatures is a scale of numbers.

To assign numbers to temperatures we select some suitable substance, then some property of this selected thermometric substance, and finally some function relating the temperature and this property. The temperature scale so defined will be only one of a large number of possible ones. It will depend in general on all three selections—the thermometric substance, the property, and the function. The property may be the length of a definite piece of metal, the volume of a definite quantity of mercury held in a definite solid, the pressure exerted by a definite mass of a definite gas at a definite volume, the electrical resistance of a definite piece of wire, etc. Any such thermometric device ceases to be useful for defining a scale if its thermometric property ceases to change as heat is abstracted from it or it undergoes such changes owing to use that, when it returns to its original thermal state after such use, it gives a reading differing significantly from the original one.

Suppose we select as basic fixed points the melting point of ice, ice point, and the boiling point of water, steam point, each at a pressure of one standard atmosphere (1,013,250 dynes/cm^2), and assign to these temperatures the numbers 0 and 100, respectively. We can define a scale by making equal increments on the scale correspond to equal increases in the length of a tungsten rod. Thus 50° would be the temperature at which the length of the rod is halfway between its length at 0° and its length at 100° or in general

$$t = 0° + \frac{L_t - L_0}{(L_{100} - L_0)/100}.$$

Are the degree intervals on this scale equal? Experience shows that the length of a rod of *copper* will be halfway between its length at 0° and its length at 100° at a temperature which on our tungsten rod expansion centigrade scale is 54°. If we divide up the interval in proportion to the change in electrical resistance, the *resistance* scale based on copper will agree with the *expansion* scale based on tungsten to within a very small fraction of a degree. The resistance scale based on tungsten agrees with none of the

other three. Which property divides the scale equally, which material? Aside from this the linear function chosen, even though the simplest choice, is entirely arbitrary.

This illustrates a fundamental property of temperature which is often lost sight of; namely, that temperature is an intensive and not an extensive quantity. There can be no unit temperature interval, which can be successively applied to measure any other temperature interval as can be done in the measurement of such a quantity as length. The size of a degree on one part of a scale, *no matter how defined*, can bear no relation to the size of a degree on any other part of the scale.

The various temperature scales that have been and still are in use differ in the thermometric substance employed, the thermometric property utilized, or in the function selected to represent the relation between the property and the temperature. Scales which differ in either of the first two features are fundamentally different. The difference between two scales, which differ only in the function chosen, is only superficial because conversion from one scale to the other is merely a matter of calculation and can be made with mathematical precision.* Changing the numbers assigned to the fixed points makes no real change in the *character* of the scale and is perhaps the simplest way that the interpolation function can be changed. Thus we have the centigrade, Fahrenheit, and Réaumur scales on which the *fundamental interval* from the ice point to the steam point is divided, respectively, into 100, 180, and 80 intervals of 1° each. In the original forms, the ice point was designated, respectively, 0°C, 32°F, and 0°R, and conversion from one scale to the other is made as follows:

$$n°\text{C} = (0.8n)°\text{R} = (1.8n+32)°\text{F}. \qquad (1)$$

It is sometimes convenient to increase all the numbers for temperatures on the above scales by a suitable, constant amount, in order that the lower limit of temperature ("absolute zero") shall be designated as 0°. The amount by which a scale should be increased to accomplish this result depends upon the thermometric property and cannot be known exactly, since it must be experimentally determined. However, since the amount by which a scale has been shifted in any given case is known, this shift can be taken care of also with mathematical precision.

On the other hand, two scales which employ either different thermometric substances or different thermometric properties differ by an amount which can be determined only by experiment. If the same basic fixed points are employed the scales will necessarily agree at these points but not at other points. Two scales both based on the apparent expansion of mercury in glass will differ unless the kind of glass used is the same. The scale based on the change in pressure, at constant volume, of a definite mass of nitrogen differs from the scale based on the change in volume of the same gas at constant pressure. The constant volume nitrogen scale with initial pressure (at the ice point) of 500 mm of mercury differs from the constant volume nitrogen scale with 1000 mm initial pressure.

Mercury-in-glass thermometry is limited to the range from the freezing point of mercury to the softening point of glass, while gas thermometry becomes difficult at very low temperatures and is limited at the high temperature end by difficulties of keeping the gas confined. A scale based on electrical resistance likewise becomes useless at "superconducting" temperatures, while at high temperatures the resistance will change at constant temperature due to permanent changes occurring in the metal even when still far removed from the melting point.

The ideal temperature scale would be one which made use of a property so selected that the scale would not depend upon the thermometric substance. Such a scale would serve throughout the entire temperature range since no limitations due to failure or breakdown of any substance would be met. The only scales of this kind that have so far been devised will now be described.

III. Carnot's Cycle

Carnot,[1] who used a p-v (pressure-volume) diagram and introduced the concept of a cycle, was interested in the problem of the efficiency

* Two scales which are based upon the same thermometric property and the same thermometric substance but upon different fixed points are not considered here. In this case the difference is fundamental only in the sense that conversion from one scale to the other can be made only on the basis of experimental data.

of an engine. Upon what does it depend and how can it be increased? If a heat engine receives an amount of heat Q and does an amount of work W, its efficiency is defined as W/Q.

Consider an engine as operating around a cycle consisting of two isothermals, t_1 and t_2, and two adiabatics, Fig. 1, and let there be mechanical and thermal equilibrium at each point. Let there be two large heat-reservoirs, one "hot" corresponding to t_2 and one "cold" corresponding to t_1. In passing from A to B the working substance absorbs heat Q_2 from the hot reservoir; from B to C there is no heat transfer; from C to D the substance loses heat Q_1 to the cold reservoir; from D to A there is again no passage of heat. Result: the net external work W performed by the engine, equal to the area $ABCD$, must equal Q_2-Q_1 by the first law of thermodynamics.

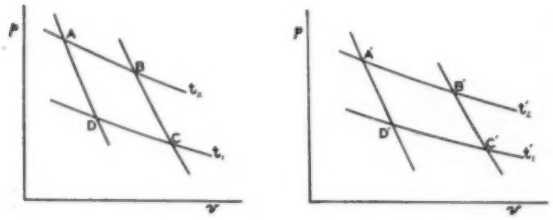


FIG. 1. Carnot's cycle.

If there is a second engine (using a different substance) working between the same two reservoirs and *any* two adiabatics we will have similarly that $W'=Q_2'-Q_1'$. Since the processes are reversible, we may couple one working directly with the other working in reverse.

Now let us choose the strokes of the two engines so that $W=W_1'$ and let the first work directly while the second works in reverse. Net result: the hot reservoir loses Q_2-Q_2', the cold reservoir gains Q_1-Q_1' and no work is done by the combination. Since the "substance" has performed a cycle it has suffered no change and the *only* result then has been a transfer of heat Q_2-Q_2' from the hotter to the colder reservoir. Experience (second law of thermodynamics), tells us that Q_2-Q_2' cannot be less than zero.

Similarly, if the second engine works directly and the first in reverse, we have that $Q_2'-Q_2$ cannot be less than zero and therefore $Q_2=Q_2'$ and since $W=W_1'$ the efficiencies of the two engines are the same, and independent of the working substance. Further, considering any one engine, its efficiency is independent of its stroke, for in the previous discussion the second engine may use the same working substance as the first and its stroke may be made to be simply an extension, on the diagram, of that of the first engine, etc. Therefore, the efficiency of an engine working in a reversible manner is independent of stroke, material, pressure, and volume, and is therefore a function only of the temperatures of the two reservoirs, i.e., of the temperature of the working substance.

$$\frac{Q_2-Q_1}{Q_2}=\frac{W}{Q_2}=f(t_1, t_2), \tag{2}$$

where t_1 and t_2 are the temperatures on *any* scale. The type of the function will, naturally, depend upon the scale adopted.

If the cycle is infinitesimal,

$$\frac{\text{area}}{Q}=f(t, t+dt). \tag{3}$$

Since area $=0$ when $dt=0$ it can be shown that

$$\frac{\text{area}}{Q}=dtf_1(t)\equiv Fdt, \tag{4}$$

where F is "Carnot's function" and Q is the heat that must be added to keep the temperature constant as the substance expands.

Any scale which employs the efficiency of a reversible heat engine as the thermometric property is therefore independent of the working substance and is known as a "thermodynamic scale."

IV. Kelvin's Original Thermodynamic Scale

William Thomson, later Lord Kelvin,[2] seized upon Carnot's principle to define a scale of temperature. Since the efficiency of a "Carnot engine" is a function of the temperatures of the reservoirs and of nothing else, Lord Kelvin proposed to number temperature intervals proportional to increments in efficiencies. Thus

$$\frac{Q_1-Q_0}{Q_1}=\frac{Q_2-Q_1}{Q_2}=\frac{Q_n-Q_{n-1}}{Q_n}=\frac{q-1}{q}\ \text{(an arbitrary constant)},$$

where the subscripts are the number of degrees above some arbitrary reference temperature θ_0, Fig. 2. From the above

$$\frac{Q_n}{Q_{n-1}}=q \quad \text{and} \quad \frac{Q_n}{Q_0}=q^n$$

or

$$n=\frac{\log Q_n-\log Q_0}{\log q},$$

and the temperature

$$\theta=\theta_0+n=\theta_0+\frac{\log Q_n-\log Q_0}{\log q}. \tag{5}$$

The ratio Q_n/Q_0 is the same for all substances and may be found by experiment. Since θ_0 and q may be arbitrarily selected, θ can be evaluated.

If the ice point be selected as the temperature to which the arbitrary value θ_0 is to be assigned, and if we wish to have a centigrade scale, i.e., 100 degrees in the fundamental interval from the ice to the steam point, q must be chosen so that

$$\frac{Q_{\text{steam}}}{Q_{\text{ice}}}=q^{100}. \tag{6}$$

For temperatures below θ_0, $Q_n<Q_0$ and, as Q_n approaches 0, θ approaches the value $-\infty$. For temperatures above θ_0, as Q_n increases θ approaches the value $+\infty$. The efficiency for $\theta>\theta_0$ is

$$\frac{Q_n-Q_0}{Q_n}=1-\frac{Q_0}{Q_n}=1-q^{-n}.$$

Therefore $\theta=+\infty$ for an efficiency of 1. Similarly for $\theta<\theta_0$ the efficiency is $1-q^n$. Therefore $\theta=-\infty$ for an efficiency of 1.

The above discussion holds for any finite value assigned to θ_0. The actual scale becomes definite as soon as a value is assigned to θ_0. Kelvin put $\theta_0=0$.

This scale did not appeal to many people because there is no similarity between the numbers assigned to temperature on this scale and on the ordinary centigrade scale. It has, however, the virtue of emphasizing the fact that when we attain a temperature of say 0.001° above absolute zero (on Kelvin's final scale), we are still far from the lowest temperature attainable.

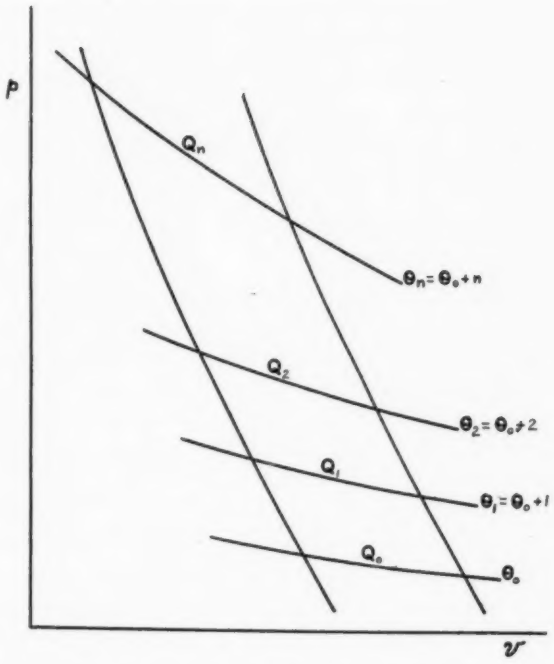


FIG. 2. Basis of Kelvin's logarithmic scale.

Kelvin's first scale can be derived in another way. Let Carnot's function F be a constant, i.e., this is the *definition* of this scale of temperature θ. In an infinitesimal cycle

$$\frac{\text{area}}{Q}=Fd\theta=\frac{dQ}{Q},$$

$$\log\left(\frac{Q}{Q_0}\right)=F(\theta-\theta_0)$$

or

$$\theta=\theta_0+\frac{\log Q/Q_0}{F}, \tag{7}$$

where θ_0 is an arbitrary number assigned to some selected thermal state and Q_0 is the heat absorbed at θ_0 in the expansion between the two adiabatics. F may be given any constant value and corresponds to $\log q$ in Eq. (5).

V. The Kelvin Scale

It is evident, then, that an indefinite number of temperature scales may be based on the efficiency of a reversible engine (thermodynamic scales) depending on the values arbitrarily assigned to θ_0 and F, to θ_0 and some second thermal state, or to F and the interval between

two selected thermal states. Let us now consider the problem of making a good selection.

The coefficient of change with temperature of any property, a, with temperature t is as follows, where α is the coefficient with reference to the temperature t_0:

$$a=a_0(1+\alpha[t-t_0]) \quad \text{i.e.,} \quad \alpha=\frac{a-a_0}{a_0(t-t_0)}. \quad (8)$$

In general, α is a function of t. Obviously α is a constant on the scale *defined by Eq.* (8) since on this "a" scale equal increments in t are defined as corresponding to equal increments in the property a. The corresponding coefficient β of any other property b is then given by

$$\beta=\frac{b-b_0}{b_0(t-t_0)}=\frac{a_0(b-b_0)}{b_0(a-a_0)}\alpha$$

on the scale of "a." Only if $(b-b_0)/(a-a_0)$ is the same for all temperatures is β independent of the temperature.

The absolute zero of this scale (the number obtained by putting $a=0$) is $t=t_0-1/\alpha$. This absolute zero has no relation to the number obtained for the lower limit of temperature. In general as heat is withdrawn a point is reached at which a ceases to change and the scale becomes useless.

Now it so happens that on our ordinary centigrade scale α is very nearly a constant for a large number of physical properties, such as the coefficient of linear expansion, the mean kinetic energy of the molecules of a gas, etc. It was desirable, therefore, from this standpoint, as well as to overcome psychological objections to any change, to select a thermodynamic scale which agreed approximately with the ordinary centigrade scales. Now from Eq. (4)

$$\text{area}=QFdt$$

and also

$$\text{area}=\left(\frac{dp}{dt}\right)_v dt(v_2-v_1);$$

hence

$$QF=\int\left(\frac{dp}{dt}\right)_v dv \quad \text{for an isothermal change.}$$

Joule applied this to the change of state, using Regnault's experiments on water and steam, and to his own experiments on the free expansion of a gas. In both cases he found that on the ordinary centigrade scale $1/F$ was very closely $t+273$. When Joule wrote Thomson about the value he had found for the Carnot function, the latter realized that by choosing F to approximate $1/t+273$ a thermodynamic scale would be obtained which approximated the ordinary centigrade scale.

Kelvin's final thermodynamic scale, known simply as the Kelvin scale, is the only one of its kind that has ever been actually used.* It was arrived at as follows.

Kelvin defined θ_m/θ_n as equal to Q_m/Q_n because then

$$\frac{Q_n-Q_m}{Q_n}=\frac{\theta_n-\theta_m}{\theta_n}$$

and for an infinitesimal area

$$\frac{\text{area}}{Q}=\frac{d\theta}{\theta}=Fdt,$$

where dt is the difference in temperature between the two reservoirs as found with an ordinary centigrade thermometer. If now $d\theta$ is chosen equal to dt then $\theta=1/F\doteq t+273$.

Kelvin's final scale becomes definite as soon as a definite number is assigned to some one thermal state or a definite number is assigned to the interval between two thermal states. For if θ_n is given, $\theta_m=(Q_m/Q_n)\theta_n$ and may be found by experiment. If $\theta_n-\theta_m$ is given

$$\theta_m=\frac{Q_m}{Q_m-Q_n}(\theta_m-\theta_n)$$

and may again be found by experiment.

The practical advantages of this scale are that (1) $\theta=t+273$ approximately if t is the temperature on an ordinary centigrade thermometer and (2) as the efficiency

$$\frac{Q_n-Q_m}{Q_n}=\frac{\theta_n-\theta_m}{\theta_n}$$

approaches unity, θ_m approaches zero and there are no negative numbers.

* The Rankine scale is essentially the same scale. Temperatures on the Rankine scale are simply 9/5 of temperatures on the Kelvin scale.

A limitation of this scale is that if we make the fundamental interval from the ice point to the steam point 100 degrees, the actual temperature of the ice point is subject to experimental determination and can therefore never be *exactly* known. (The experimental value is close to 273.16 and the actual value is almost certainly between 273.1 and 273.2.)

On the other hand if we assign 273 (or even 273.16) to the ice point, as proposed by Giauque,[3] the number of degrees in the interval from the ice point to the steam point becomes subject to experimental determination and will not be exactly 100.

Kelvin wisely chose to assign 100 degrees to the fundamental interval rather than to assign a definite number to the ice point. On this scale, known simply as the Kelvin scale, temperatures are designated as "°K" and customarily denoted by the symbol T. The ice point is denoted by T_0.

It may be of interest to compare the numbers, T, for a few temperatures on the Kelvin scale with the corresponding numbers, L, for the same temperatures on Kelvin's first (logarithmic) scale. Taking the ice point as 273.16°K

$$L=100\frac{\log T-\log 273.16}{\log 373.16-\log 273.16}=738\log T-1798.$$

A few values are given in Table I.

On the logarithmic scale therefore, the progress from the attainment of 4.22°K (the normal boiling point of helium) to the attainment of 0.005°K (reached early in 1935) is recorded as progress from -1336 to about -3500°L. This represents a tremendous advance, to be sure, but no more an approach to the lower end of the scale than the progress at the other end from the melting point of gold, 1336°K, to that of tungsten, about 3700°K, is an approach to the upper end of the scale.

If we write $t=T-T_0$, t is the temperature on a scale which is called the Thermodynamic Centigrade scale. Any temperature *interval* has the same value when expressed on this scale as when expressed on the Kelvin scale. When using the Thermodynamic Centigrade scale one is simply expressing the number of Kelvin degrees that a particular thermal state is above or below the ice point. The International Temperature

TABLE I. *Conversion table; Kelvin scale to logarithmic scale.*

T	L	T	L
∞	∞	100	-322
10^6	2630	10	-1060
10^5	1892	4.22	-1336
10^4	1154	1	-1798
3673	833	0.1	-2536
1336	509	0.01	-3274
1000	416	0.005	-3497
373.16	100	0.001	-4012
273.16	0	0	$-\infty$

scale,[4] which will be discussed later on, is a practical scale which "conforms with the Thermodynamic Centigrade scale as closely as is possible with present knowledge."

If the only thermometer which would yield temperatures on the Kelvin scale were a reversible heat engine, the scale would have no practical importance. However, if we had a gas which rigorously obeyed Boyle's law and which suffered no change of internal energy u during a change of volume at a constant temperature then a given mass of this gas would obey the law $pv=kT$ where T is now the Kelvin temperature. This gas, which is called an ideal gas, when used in either a constant pressure or constant volume gas thermometer, would yield the Kelvin scale directly.

The two conditions of ideality may be written

$$(pv)_t=\text{constant} \quad \text{and} \quad \left(\frac{du}{dv}\right)_t=\lambda=0.$$

VI. Reduction of the Scale of a Real Gas to the Kelvin Scale

1. The Joule-Thomson Effect in Gases

Gay-Lussac and later Joule made experiments which seemed to show that if a gas expands from one vessel into another vessel previously empty, the first vessel loses just as much heat as the second one gains.

Gay-Lussac used two globes, each of about 12 liters capacity, and each containing a thermometer. One vessel was exhausted and the other contained air at atmospheric pressure. On opening a connecting stopcock, one thermometer rose 0.58° while the other fell 0.61°. Joule placed two copper vessels, connected with a pipe, in a stirred water calorimeter. One vessel was exhausted and the other filled with air at 22

atmospheres. On opening a stopcock in the connecting pipe no appreciable rise in the temperature of the calorimeter was found.

Thomson realized that it was important to repeat Joule's experiments and to measure accurately the heat required to keep the temperature of a gas constant while it was expanding. If $Q=\int pdv$ exactly there are two consequences: (1) the change $(du)_t$ in the internal energy u is zero, i.e., u is a function of temperature only and (2) $T=t+1/\alpha$, where t is the temperature on the centigrade constant volume or constant pressure scale based on this gas and α is the coefficient of change of the pressure or volume referred to the ice point. He proposed a modification in Joule's experiment, which has come to be known as the porous plug experiment. The idea is to force a continuous stream of gas through a porous plug under conditions of no inflow or outflow of heat, the gas passing thus from a condition of high pressure to one of low pressure. If the rate of flow is kept small, the effect of the directed kinetic energy is negligible. If there is any change of temperature noted, a calculation can be made as to how much heat must be added to bring the gas back to its original temperature. Thus an isothermal process may be studied.

In Fig. 3, let $p_1>p_2$. p = pressure; t = temperature; v = volume of unit mass; u = internal energy of unit mass.

The numerical subscripts refer to the condition of the gas, while the letter subscripts indicate that the property denoted by the subscript is held constant. Thus c_p is the specific heat at constant pressure, etc. Small letters refer to unit mass of gas. As unit mass of gas passes through the plug the net work done on the gas is equal to the increase in the internal energy, since $\Delta Q=0$.

$$p_1v_1-p_2v_2=u_2-u_1. \tag{9}$$

In order to restore the temperature to t_1, keeping the pressure p_2, the heat* to be added is

$$c_p(t_1-t_2)=u_2'-u_2+p_2(v_2'-v_2), \tag{10}$$

where u_2' and v_2' refer to pressure p_2 and temperature t_1.

* In another form of the experiment, heat is added during the experiment and the amount so regulated that the temperature of the gas on the two sides of the plug is the same. In this case measurement of the rate of gas flow and heat input yields the product μc_p.

Substituting in Eq. (9) the value of u_2 from Eq. (10)

$$u_2'-u_1=p_1v_1-p_2v_2'+c_p(t_1-t_2), \tag{11}$$

i.e.,
$$du_t=-d(pv)_t-c_pdt. \tag{12}$$

Thus, if Boyle's law holds, i.e., if pv is a constant at uniform temperature, and if $t_2=t_1$ in the porous plug experiment, $du=0$ for an isothermal change and u is a function only of t. Otherwise du may be evaluated from the observations of Δt and $\Delta(pv)_t$.

Thomson showed how to calculate the numerical value of T for any one temperature by means of this experiment.

$$(du+pdv+vdp)_t=-c_pdt. \tag{13}$$

Since increase in u = heat added (Δq) + work done on the gas $(-pdv)$

$$du=\Delta q-pdv \tag{14}$$

$$\left(\frac{\Delta q}{dp}+v\right)_t=-c_p\frac{dt}{dp}=-\mu c_p,$$

where μ is the "Joule-Thomson coefficient."

$$\frac{\text{area}}{Q}=\frac{dT}{T},$$

where Q is the heat added to keep the temperature constant as pressure is decreased from p_1 to p_2

$$Q=-\left(\frac{\Delta q}{dp}\right)_t dp,$$

$$\text{area}=\left(\frac{dv}{dT}\right)_p dTdp;$$

$$\therefore\quad \left(\frac{\Delta q}{dp}\right)_t=-T\left(\frac{dv}{dT}\right)_p.$$

Hence

$$-T\left(\frac{dv}{dT}\right)_p+v=-\mu c_p;$$

$$\therefore\quad -\frac{1}{T}\left(\frac{dT}{dv}\right)_p+\frac{v}{T^2}=-\frac{\mu c_p}{T^2}.$$

Integrating with respect to T

$$\left[\left(\frac{v}{T}\right)_2-\left(\frac{v}{T}\right)_1\right]_p=\int_1^2\frac{\mu c_p}{T^2}dT. \tag{15}$$

Suppose we measure t on the scale based on the expansion at constant pressure of the same gas used in the porous plug experiment, i.e., $v=v_0(1+\alpha t)$ is the definition of this scale, where α is a constant and v_0 is the volume at the ice point, $t_0=0°$.

$$\frac{v}{t+1/\alpha}=v_0\alpha=\text{a constant}$$

and

$$\left[\left(\frac{v}{t+1/\alpha}\right)_2-\left(\frac{v}{t+1/\alpha}\right)_1\right]_p=0.$$

Now, since T is known to be nearly $t+1/\alpha$ (of Eq. (15)), μ is a very small quantity, or conversely if it is granted that μ is a small quantity $T=t+1/\alpha$ approximately.

As a first approximation t may be replaced by $T-273$ in the empirical relation expressing μ as a function of t and p found from the porous plug experiment. The integration of Eq. (15) between two definite temperatures, say the ice and steam points, then yields

$$\left[\left(\frac{v}{T}\right)_2-\left(\frac{v}{T}\right)_1\right]_p=J_2-J_1.$$

1. Applying to the limits 0° and 100°C and defining $T_{\text{steam}}-T_{\text{ice}}=100$,

$$v_{100}=v_0(1+100\alpha) \text{ by definition.}$$

$$\frac{v_0(1+100\alpha)}{T_0+100}-\frac{v_0}{T_0}=J_{373}-J_{273}$$

$$T_0=\frac{1}{\alpha}+\frac{T_0(T_0+100)}{100v_0\alpha}(J_{373}-J_{273})$$

$$=\frac{1}{\alpha}+\frac{273\times373}{100v_0\alpha}(J_{373}-J_{273})$$

$$=\frac{1}{\alpha}+\epsilon_0,$$

where ϵ_0 is a very small quantity found from the porous plug experiment.

2. Applying to the limits 0° and t°C

$$v=v_0(1+\alpha t)$$

by definition of t at constant pressure. Let

$$T=T_0+t+\delta, \qquad (16)$$

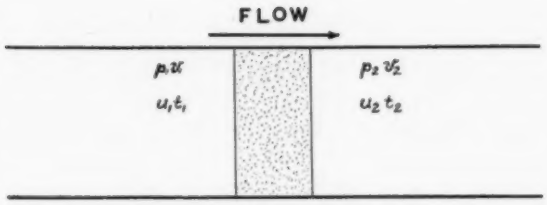


FIG. 3. Illustration of the Joule-Thomson porous plug experiment.

$$\frac{v_0(1+\alpha t)}{T_0+t+\delta}-\frac{v_0}{T_0}=J_{t+273}-J_{273}.$$

Substitute

$$T_0=\frac{1}{\alpha}+\epsilon_0,$$

$$\delta=\epsilon_0\alpha t-\frac{273(t+273)}{v_0}(J_{t+273}-J_{273}).$$

We may now as a second approximation use the relation found from the first calculation instead of the relation $T=t+1/\alpha$ and repeat the calculation to secure a more exact relation etc. Actually it turns out that the first approximation is sufficient. Measurements of α and μ for a number of gases yield the result that the ice point is between 273.1 and 273.2 on the Kelvin scale.

The calculation is valid, of course, only for values of t at which the empirical formula for μc_p holds, namely where experiments can be made, and where the approximation $t=T-273$ is justified; namely, where the gas does not depart very far from Boyle's law.

It is to be noted that the porous plug experiment measures a single quantity which depends on the departure of the gas from both conditions of ideality. A knowledge of μ and c_p enables us to correct the results obtained with the constant pressure form of gas thermometer.

The equation, corresponding to (15), for the constant volume thermometer is

$$\left[\left(\frac{p}{T}\right)_2-\left(\frac{p}{T}\right)_1\right]_v=\int_1^2\frac{\lambda}{T^2}dT.$$

Determinations of $\lambda=(du/dv)_t$ in the range of pressures of interest in gas thermometry indicate that λ is small.

2. Berthelot's Method

Berthelot devised a method which does not require a knowledge of μc_p or λ and is the one used in correcting practically all gas thermometer measurements.

The absolute temperature shown by a thermometer filled with any real gas defined by the relation

$$pv = \text{constant} \times \text{temperature} \qquad (17)$$

may be denoted by T_v or T_p according as the volume or the pressure is kept constant. For an ideal gas we should have

$$T_v = T_p = T, \qquad (18)$$

where T again denotes temperature on the Kelvin scale, and the more closely the actual gas approaches the ideal state, or the smaller the departures from the specified properties of the nonexistent ideal gas, the more nearly will Eq. (18) be true for the gas in question.

For the more permanent gases, e.g., helium, neon, argon, hydrogen, and nitrogen, these departures are small and decrease as the density of the gas is diminished. Consequently a thermometer filled with one of these gases and used at either constant volume or constant pressure gives a first approximation to a realization of the Kelvin scale, and the approximation improves as the density of the gas is lowered.

The corrections, $T-T_v$ or $T-T_p$, may be found from the results of auxiliary experiments on the properties of the gases which determine how far these properties depart from those assigned, by definition, to the ideal gas. Over the temperature ranges in which they have been investigated, these corrections are small (usually negligible in comparison with the precision attainable in gas thermometry).

Berthelot's method relies on measurements of compressibility at constant temperatures. It is based upon two postulates (1) that the gas approaches the ideal state as its density approaches 0, so that $T_v \doteq T_p \doteq T$ and (2) that the extrapolation—whether graphical or analytical—from the lowest measured values of p to $p=0$ is permissible.

The method amounts, in principle, to drawing the isothermals $pv=f(p)$ from observations at known and reproducible temperatures, and extrapolating them to $p=0$, so as to find their intercepts on the pv axis.

From Fig. 4, $T_p \doteq T_v$ when $p \doteq 0$. Let AA' and BB' be the isothermals determined by experiment at the temperatures t_1 and t_2. Then if the constant pressure thermometer is used at the pressure p_0

$$\frac{(T_p)_2}{(T_p)_1} = -\frac{FE}{FC},$$

while if the constant volume thermometer is used with the pressure p_0 at the lower temperature

$$\frac{(T_v)_2}{(T_v)_1} = \frac{OD}{OC}.$$

These ratios, obviously, approach each other as p_0 approaches 0.

If the two postulates stated above hold for the gas used the ratio T_2/T_1 is therefore given by OB/OA and can be found for any two temperatures.

The first postulate will hardly be questioned by any one. The second amounts to assuming that the isothermals do not suffer any sudden changes of direction at pressures below those at

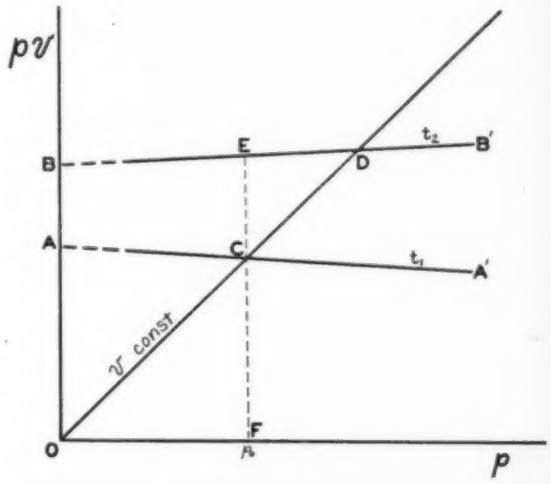


Fig. 4. Berthelot's method.

which accurate measurements of $pv=f(p)$ can be made. This seems also to be subject to very little doubt. If t_1 and t_2 are any two reproducible temperatures, compressibility experiments carried

out at these temperatures on the same mass of gas yield the ratio T_2/T_1 directly, without any reference to T_v or T_p.

In his paper Berthelot did the work algebraically instead of graphically. By setting up a general reduced equation, he coordinated the available experimental data on various gases, the only requirement being that the equation should hold for the low pressures used in gas thermometry.

If the compressibility data on any one gas are accurate enough and cover the desired range of temperature, the use of a general reduced equation of state is unnecessary, and the objectionable assumption of a law of corresponding states* is avoided. The two original postulates remain and their existence should not be ignored. Nevertheless, this method is probably the most accurate available for determining the ratios of any two values of T. The constant-pressure method of gas thermometry has not been used much in recent years. The constant-volume hydrogen and helium thermometers have been used successfully below 0°C. At moderately high temperatures, the materials used for the bulbs appear to become permeable to hydrogen and helium and to react with hydrogen, so that exact work with them has not been done above about 100°C. For higher temperatures nitrogen is found satisfactory.

TABLE II.

EXPERIMENTERS	YEAR	VALUE OBTAINED
Barus	1892	1093°C
Holborn and Wien	1895	1072
Holborn and Day	1901	1063.5
Jaquerod and Perrot	1905	1067.2
Day and Clement	1907	1059.3
Day and Sosman	1912	1062.4

The corrections to the constant volume nitrogen scale for an initial (ice point) pressure of 1000 mm of mercury are about 0.2°K at 700°K and about 1°K at 1500°K. These corrections, being proportional to the initial pressure, are smaller for the pressures used in high temperature gas thermometry. Thus in their work on the gold point, 1336°K, Day and Sosman used initial pressures of 217 and 345 mm of mercury.

While a high degree of accuracy cannot be claimed for the corrections, it is to be emphasized that they are small. The corrections to the experimentally determined values of T for the melting point of gold are only about 0.2 or 0.3°K, so that an error of even 50 percent in these corrections is not a serious matter.

VII. High Temperature Gas Thermometry

The nitrogen constant volume scale has been extended up to 1550°C by Day and Sosman[5] by a monumental work during which they determined the melting point of palladium as 1549.2°C on this scale. It is very improbable that their work will be repeated for a long time to come. The difficulties are too great. They estimate ±2° as the accuracy of this determination. The importance of their classic work can scarcely be overestimated. Their value for the palladium point yields an important check on the laws of radiation, and their determination of T for the melting point of gold, or "gold point," is largely the basis for our present high temperature scale.

There have been a number of determinations of the gold point on various gas thermometer scales. The results of some are listed in Table II.

The values obtained before the beginning of the present century are now of only historical interest. In fact only those of Holborn and Day, obtained at the Reichsanstalt in Berlin and of Day and Sosman, obtained at the Geophysical Laboratory in Washington, should be considered. On this basis we know that the gold point is within 1°, probably within 0.5°, of 1336°K.

The next step is to extend this scale, with the gold point = 1336°K as a basis, to higher temperatures.

VIII. Optical Methods of Temperature Measurement

1. THE BLACKBODY

Imagine a hollow enclosure impervious to heat from without. If left to itself it will come to a uniform temperature, in accordance with the second law of thermodynamics, provided there is a possibility of interchange of heat between all parts of its inner wall. This presupposes that a

* In the more special form announced by van der Waals it says that if the pressures, volumes, and absolute temperatures be expressed as ratios of their values at the critical point, the equation of state is the same for all substances and contains no quantities dependent on the special properties of particular substances.

portion at least of the interior surface emits and absorbs, to some extent, all *wave-lengths*, and that no portion is a perfect reflector.**

When a state of constant and uniform temperature is reached, *the radiant energy at any point inside such an enclosure is independent of the nature of the walls*. To prove this, consider the following processes:

a. Place inside the enclosure a spherical body whose surface is totally reflecting with the exception of a minute element which is totally absorbing, i.e., "black." After a time there is temperature equilibrium throughout both enclosure and spherical body. In this state, the energy E_s emitted by the spherical body per unit time must equal that which it absorbs E, the latter quantity being the energy falling upon the "black" element of the spherical body and coming from the walls of the enclosure. E_s must be a property of the spherical body and must therefore remain unchanged if its temperature is not changed.

b. Now alter the character of a portion of the wall of the enclosure, keeping its temperature unchanged, e.g., make it "black." The existing temperature is unaffected and therefore E_s is unchanged since the spherical body is unaffected; hence E is unchanged.

c. If the sphere be now rotated so that the black element is brought into a new position and is facing in a new direction, the temperature equilibrium is again unaffected and E_s is unchanged. That is, *the flux of radiant energy at all points and in all directions inside the enclosure is identically the same*.

It may be similarly demonstrated that the quality (as regards "polarization") and distribution of radiant energy among the various wave-lengths is likewise independent of everything except temperature. We can, in such cases, speak of the *temperature of the radiant energy*.

The radiant energy inside an enclosure at constant and uniform temperature is called "blackbody radiation." Any body which emits blackbody radiation is called a "blackbody." The energy emerging from an opening in the walls of an enclosure such as described above approaches blackbody radiation as the opening is made smaller and smaller. Such a small opening is, for all practical purposes, a blackbody.

2. Kirchhoff's Law

Consider the radiation E_λ of any definite wave-length λ along a line joining any element of the wall with any element of the enclosed body. In either direction it is the same and is that characteristic of a blackbody. Of the energy E_λ falling on it the element of the enclosed body will absorb an amount $A_\lambda E_\lambda$, reflect an amount $r_\lambda E_\lambda$, and transmit an amount $t_\lambda E_\lambda$. Let

$$G_\lambda = r_\lambda E_\lambda + t_\lambda E_\lambda = (1 - A_\lambda) E_\lambda. \qquad (19)$$

In the other direction the radiant energy coming from the element of the enclosed body is made up of the part emitted $(E_s)_\lambda$ and the part reflected or transmitted

$$G_\lambda' = r_\lambda E_\lambda + t_\lambda' E_\lambda = E_\lambda - (E_s)_\lambda. \qquad (20)$$

The reflected part is obviously the same in the two cases, but the transmitted parts $t_\lambda E_\lambda$ and $t_\lambda' E_\lambda$ are traveling in opposite directions. From the laws of optics, however, $t_\lambda = t_\lambda'$.

If we define the spectral emissivity, e_λ, of a body as the ratio of the energy of wave-length λ radiated by the body to that radiated by a blackbody at the same temperature $(E_s)_\lambda = e_\lambda E_\lambda$. ($e_\lambda$ for any body is a function of both λ and temperature.)

Then $G_\lambda' = G_\lambda$ and

$$E_\lambda - (E_s)_\lambda = (1 - e_\lambda) E_\lambda = (1 - A_\lambda) E_\lambda. \qquad (21)$$

Hence $e_\lambda = A_\lambda$. This is Kirchhoff's law.† Therefore a body at a given temperature emits an amount of radiation $(E_s)_\lambda = e_\lambda E_\lambda$, which is equal to blackbody radiation of this temperature which it will absorb $A_\lambda E_\lambda$. This law is used in the measurement of flame temperature by the line reversal method.

3. The Laws of Radiation

There have been many investigations, both experimental and theoretical, to determine how the distribution of energy in the spectrum of a

** The existence of a perfectly reflecting portion does not affect the character of the radiant energy inside the space and therefore such a portion, if present, may be disregarded. The second of the above conditions is essential only to the process of attaining a uniform temperature.

† It must be noted that Kirchhoff's law is based upon the postulate that (E_s) is a property of the body and does not depend upon the radiation falling upon it. Kirchhoff's law, therefore is not true for fluorescent bodies for which this postulate is not fulfilled.

blackbody depends on wave-length and temperature. On the basis of "classical mechanics" and certain postulates regarding the mechanism of radiation Wien deduced the formula

$$J_{\lambda T}=\frac{c_1}{\lambda^5 e^{c_2/\lambda T}} \quad \text{Wien's formula}$$

in which λ is the wave-length, T is the temperature in degrees K, e is the Naperian base $2.71828\cdots$ and $J_{\lambda T}$ is the radiant energy (of wave-length λ) per unit wave-length interval emitted per unit time by unit area of a blackbody at temperature T throughout the solid angle 2π, i.e., "hemispherical radiation."

According to this formula, $J_{\lambda T}$ does not increase without limit as T increases for finite values of λ because when $T=\infty$, $J_{\lambda T}=c_1\lambda^{-5}$. In 1900 Rubens and Kurlbaum made measurements at very long wave-lengths and found that at $\lambda=0.005$ cm their results deviated from Wien's formula by 40 percent at $T=1773$ to several hundred percent at low temperatures. It is reported that when they wrote to Planck, who was on vacation, the latter replied on a postcard: "Try adding minus one to the denominator." This was the conception of the quantum theory.

Planck's formula,

$$J_{\lambda T}=\frac{c_1}{\lambda^5(e^{c_2/\lambda T}-1)}, \tag{22}$$

fitted the observations of Rubens and Kurlbaum at $\lambda=0.005$ cm within 4 percent from $T=85°$K to $T=1773°$K.

The birth of the quantum theory occurred when Planck attempted to derive his formula theoretically and found that it could not be done without postulating that energy is radiated only in multiples of a finite quantity $\epsilon=h\nu$, h being a constant and ν the frequency.

Planck's derivation[6] is not considered valid today. However, a rigorous derivation results from the application of modern quantum statistics and our main interest is in the fact that, today, the validity of Planck's formula is not questioned. We therefore have a means of extending the Kelvin scale upward without limit.

The maximum value of $J_{\lambda T}$ is easily found to be at

$$\lambda_{\max}=\frac{c_2}{4.9651T}. \tag{23}$$

Furthermore

$$\int_0^\infty J_{\lambda T}d\lambda=\sigma T^4, \tag{24}$$

which is the Stefan-Boltzmann law. Any one of the three formulas (22), (23), or (24) will yield the Kelvin scale.

The various constants involved are related as follows:

$$c_1=2\pi c^2h=\frac{15}{\pi^4}\sigma c_2^4, \tag{25}$$

$$c_2=\frac{ch}{k}=\left(\frac{h}{e}\right)\frac{cF}{R}, \tag{26}$$

and

$$\sigma=\frac{2\pi^5c^2h}{15c_2^4}=40.8026\frac{c^2h}{c_2^4}, \tag{27}$$

where c = the velocity of light in cm sec.$^{-1}$;
h = Planck's constant of action in erg sec.;
k = the Boltzmann constant in erg deg.$^{-1}$;
e = electronic charge in electrostatic units (e.s.u.);
F = the Faraday constant in (e.s.u.) mole^{-1};
R = the gas constant in erg deg.$^{-1}$ mole^{-1}.

4. Optical Pyrometry

Inasmuch as absolute measurements of radiant energy are difficult and inaccurate whereas relative values can easily be measured with considerable accuracy, the following equation, which follows directly from Eq. (22), is in the form useful for optical pyrometry.

$$R_\lambda=\frac{J_{\lambda T_1}}{J_{\lambda T_2}}=\frac{e^{c_2/\lambda T_2}-1}{e^{c_2/\lambda T_1}-1}. \tag{28}$$

It is evident that if we know c_2 and the value of T for some fixed point at which a blackbody emits sufficient light for the purposes of optical pyrometry the problem of extending the Kelvin scale upward in practice is solved. It is also evident that if we know the values of T for two suitable fixed points a measurement of R_λ for any value of λ with an optical pyrometer will serve to determine c_2. Six such suitable fixed points have been determined by gas thermometry.[7]

The value of c_2 may also be found, using Eq. (23), from a knowledge of T and $\lambda_{\max}$ for one

fixed point. Similarly c_2 may be found from Eq. (27) from measurements of σ as defined in Eq. (24). Finally, c_2 may be calculated from the various atomic constants in Eq. (26). The values obtained are given in Table III which is taken from a review[7] of the experimental data.

TABLE III. *Summary of values of c_2 from all sources.*

SOURCE	c_2 IN CM DEG.	WEIGHT
$\lambda_m T$	1.4361±0.0050	1
σ	1.4368± .0040	1
Optical pyrometry	1.4364± .0020	2
Atomic constants	1.4358± .0015	3
Weighted mean	1.4362±0.001	
Mean deviation	0.0003	

IX. The International Temperature Scale

The International Temperature scale, unanimously adopted in 1927 by the Seventh General Conference of Weights and Measures (representing 31 nations), is based on a number of fixed points whose location on the Kelvin scale relative to the ice point has been determined by gas thermometers. Part I of the text of the scale, given below, is self-explanatory. A few editorial corrections, not affecting the scale itself, were made in 1933.

DEFINITION OF THE INTERNATIONAL TEMPERATURE SCALE

1. The Thermodynamic Centigrade scale, on which the temperature of melting ice, and the temperature of condensing water vapor, both under the pressure of one standard atmosphere, are numbered 0° and 100°, respectively, is recognized as the fundamental scale to which all temperature measurements should ultimately be referable.

2. The experimental difficulties incident to the practical realization of the thermodynamic scale have made it expedient to adopt for international use a practical scale designated as the International Temperature scale. This scale conforms with the thermodynamic scale as closely as is possible with present knowledge, and is designed to be definite, conveniently and accurately reproducible, and to provide means for uniquely determining any temperature within the range of the scale, thus promoting uniformity in numerical statements of temperature.

3. Temperatures on the international scale will ordinarily be designated as "°C," but may be designated as "°C (Int.)" if it is desired to emphasize the fact that this scale is being used.

4. The International Temperature scale is based upon a number of fixed and reproducible equilibrium temperatures to which numerical values are assigned, and upon the indications of interpolation instruments calibrated according to a specified procedure at the fixed temperatures.

5. The basic fixed points and the numerical values assigned to them for the pressure of one standard atmosphere are given in the following table, together with formulas which represent the temperature (t_p) as a function of vapor pressure (p) over the range 680 to 780 mm of mercury.

6. Basic fixed points of the International Temperature scale—

	°C
(*a*) Temperature of equilibrium between liquid and gaseous oxygen at the pressure of one standard atmosphere (oxygen point) $t_p=t_{760}+0.0126(p-760)-0.0000065(p-760)^2$.	−182.97
(*b*) Temperature of equilibrium between ice and air-saturated water at normal atmospheric pressure (ice point)	0.000
(*c*) Temperature of equilibrium between liquid water and its vapor at the pressure of one standard atmosphere (steam point) $t_p=t_{760}+0.0367(p-760)-0.000023(p-760)^2$.	100.000
(*d*) Temperature of equilibrium between liquid sulphur and its vapor at the pressure of one standard atmosphere (sulphur point) $t_p=t_{760}+0.0909(p-760)-0.000048(p-760)^2$.	444.60
(*e*) Temperature of equilibrium between solid silver and liquid silver at normal atmospheric pressure (silver point)	960.5
(*f*) Temperature of equilibrium between solid gold and liquid gold at normal atmospheric pressure (gold point)	1063

Standard atmospheric pressure is defined as the pressure due to a column of mercury 760 mm high, having a density of 13.5951 g/cm³, subject to a gravitational acceleration of 980.665 cm/sec.² and is equal to 1,013,250 dynes/cm².

It is an essential feature of a practical scale of temperature that definite numerical values shall be assigned to such fixed points as are chosen. It should be noted, however, that the last decimal place given for each of the values in the table is significant only as regards the degree of reproducibility of that fixed point on the International Temperature scale. It is not to be understood that the values are necessarily known on the Thermodynamic Centigrade scale to the corresponding degree of accuracy.

7. The means available for interpolation lead to a division of the scale into four parts.

(*a*) From the ice point to 660°C the temperature t is deduced from the resistance R_t of a standard platinum resistance thermometer by means of the formula

$$R_t=R_0(1+At+Bt^2).$$

The constants R_0, A, and B of this formula are to be determined by calibration at the ice, steam, and sulphur points, respectively.

The purity and physical condition of the platinum of which the thermometer is made should be such that the

ratio R_t/R_0 shall not be less than 1.390 for $t=100°$ and 2.645 for $t=444.6°$.

(*b*) From $-190°$ to the ice point, the temperature t is deduced from the resistance R_t of a standard platinum resistance thermometer by means of the formula

$$R_t=R_0[1+At+Bt^2+C(t-100)t^3].$$

The constants R_0, A, and B are to be determined as specified above, and the additional constant C is determined by calibration at the oxygen point.

The standard thermometer for use below 0°C must, in addition, have a ratio R_t/R_0 less than 0.250 for $t=-183°$.

(*c*) From 660°C to the gold point, the temperature t is deduced from the electromotive force e of a standard platinum *vs.* platinum-rhodium thermocouple, one junction of which is kept at a constant temperature of 0°C while the other is at the temperature t defined by the formula

$$e=a+bt+ct^2.$$

The constants a, b, and c are to be determined by calibration at the freezing point of antimony, and at the silver and gold points.

(*d*) Above the gold point the temperature t is determined by means of the ratio of the intensity J_2 of monochromatic visible radiation of wave-length λ cm, emitted by a blackbody at the temperature t_2, to the intensity J_1 of radiation of the same wave-length emitted by a blackbody at the gold point, by means of the formula

$$\log_e\frac{J_2}{J_1}=\frac{c_2}{\lambda}\left[\frac{1}{1336}-\frac{1}{(t+273)}\right].$$

The constant c_2 is taken as 1.432 cm degrees. The equation is valid if $\lambda(t+273)$ is less than 0.3 cm degrees.

The statement that the International scale "conforms with the thermodynamic (centigrade) scale as closely as is possible with present knowledge" is not entirely true today. The introduction to the scale stated that the scale "is to be regarded as susceptible of revision and amendment as improved and more accurate methods of measurement are evolved."

The International Conference, meeting every six years, was scheduled to consider revision of the temperature scale in October 1939, but failed to meet in 1939 on account of the unsettled political conditions. Among the revisions by which the conformity with the thermodynamic scale might be improved are (1) the substitution of Planck's formula (28) for the form of Wien's formula given in the scale, (2) the use of a slightly higher value for c_2, (3) some modification in values assigned to some of the fixed points to make departures from the thermodynamic scale smaller and more regular, (4) making the junction between the thermocouple and the resistance thermometer ranges at the freezing point of antimony instead of at 660°C, (5) extension of the scale below $-190°$C, and (6) better specifications for the standard resistance thermometer.

None of these revisions, with the exception of (4) and (5), would make the scale more useful. Its greatest usefulness lies in the fact that its universal use has practically eliminated ambiguities in the specification of temperatures. If and when the scale is modified, the resulting differences will be known and conversion from the 1927 scale to the modified scale can be easily made. If for some time during and after such a modification, people are careful to state on which scale temperatures are being specified, no confusion should occur. The first requirement of any scale is that it provide means by which any thermal state may be unambiguously specified.

Bibliography

1. Published in 1824 in a work entitled *Reflexions sur la Puissance Motrice du Feu*, by M. S. Carnot.
2. W. Thomson, Phil. Mag. **33**, 313 (1848).
3. W. F. Giauque, Nature **143**, 623 (1939).
4. George K. Burgess, Nat. Bur. Stand. J. Research **1**, 635 (1928).
5. Day and Sosman, Carnegie Inst. Wash. Pub. 157 (1911)
6. M. Planck, Ann. d. Physik **309**, 553 (1901).
7. H. T. Wensel, Nat. Bur. Stand. J. Research **22**, 375 (1939).

Thermoelectric Thermometry*

By Wm. F. Roeser

National Bureau of Standards, Washington, D. C.

The fundamental laws and theories of thermoelectric phenomena and their historical development as well as the application of these phenomena to the measurement of temperature are discussed in this paper in considerable detail. Thermoelectric thermometry, with particular regard to types of thermocouples, protection of thermocouples, fundamental considerations in temperature measurements, etc. are treated primarily from the practical standpoint.

I. Introduction

STUDY in the field of thermoelectricity began in 1821 with the discovery of Seebeck[1] that an electric current flows continuously in a closed circuit of two dissimilar metals when the junctions of the metals are maintained at different temperatures. In the early investigations of thermoelectric effects the results were expressed more qualitatively (in terms of the direction of the current flowing in a closed circuit) than quantitatively, because the relations between the measurable quantities in an electric circuit were not well known at the time.†

II. Fundamental Laws

As a result of a large number of investigations of thermoelectric circuits in which accurate measurements were made of the electromotive force, current, and resistance, several "established facts" or "laws" have been formulated. These facts or laws, variously stated in different ways and combinations and sometimes consolidated into a general statement of the phenomenon discovered by Seebeck, can be reduced to three fundamentals:

(1) The law of the homogeneous circuit
(2) The law of intermediate metals
(3) The law of successive or intermediate temperatures.

The latter two may be arrived at by applying the laws of thermodynamics to the thermoelectric circuit, but the fundamental experimental fact regarding a homogeneous circuit, which enters into all measurements of temperature by thermoelectric methods, cannot be derived from such considerations. The law of the homogeneous circuit is incorporated into most statements of the law of intermediate metals. In any case all of these facts or laws, as stated below and used in the measurement of temperatures, have been established experimentally beyond a reasonable doubt and in order that temperatures may be measured by this method the laws must be accepted in spite of any lack of rigor that may appear in any of the thermodynamic derivations given here or elsewhere.

The discussion will be simplified by defining a few terms at this point. It will be considered that all the metals comprising a thermoelectric circuit are solids unless otherwise stated.

A pair of electrical conductors so joined as to produce a thermal e.m.f. when the junctions are at different temperatures is known as a thermocouple. The resultant e.m.f. developed by the thermocouples generally used for measuring temperatures ranges from 1 to 7 millivolts when the temperature difference between the junctions is 100°C.

If in a simple thermoelectric circuit, Fig. 1, the current flows from metal A to metal B at the colder junction, A is generally referred to as thermoelectrically positive to B. In determining or expressing the e.m.f. of a thermocouple as a

* Presented at the American Institute of Physics Symposium on Temperature, Its Measurement and Control in Science and Industry, November 4, 1939.

† The relation between the current and potential difference in an electric circuit was first clearly stated by G. S. Ohm in 1826. Schweigger's J. **46**, 137 (1826).

function of the temperature, one junction is maintained at some constant reference temperature, such as 0°C, and the other is at the temperature corresponding to the e.m.f. In the present paper, the order in which the metals are named and the sign of the numerical value of the e.m.f. will be used to indicate which of the metals is

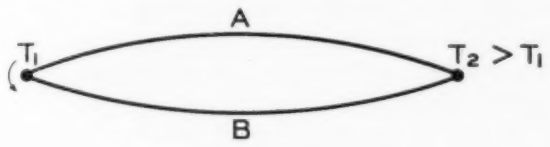


FIG. 1. Simple thermoelectric circuit.

positive to the other at the junction which is at the reference temperature. For example, if, in Fig. 1, T_1 is the reference temperature and the current flows in the direction indicated, the e.m.f. of thermocouple AB will be positive, and the e.m.f. of thermocouple BA will be negative.

1. The Law of the Homogeneous Circuit

An electric current cannot be sustained in a circuit of a single homogeneous metal, however varying in section, by the application of heat alone. As far as we know this principle has not been derived theoretically. It has been claimed from certain types of experiments that a nonsymmetrical temperature gradient in a homogeneous wire gives rise to a galvanometrically measurable thermoelectric e.m.f. However, the overwhelming weight of evidence indicates that any e.m.f. observed in such a circuit is to be attributed to the effects of local inhomogeneities. As a matter of fact, at the present time any current detected in such a circuit when the wire is heated in any way whatever, is taken as evidence that the wire is inhomogeneous. The more important of a large number of investigations of this subject are adequately discussed by Foote and Harrison.[2]

In the present paper, we accept, as an experimental fact, the general statement that the algebraic sum of the electromotive forces in a circuit of a single homogeneous metal however varying in section and temperature is zero. As a consequence of this fact, if one junction of two dissimilar homogeneous metals is maintained at a temperature T_1 and the other junction at a temperature T_2, the thermal e.m.f. developed is independent of the temperature gradient and distribution along the wires.

2. Law of Intermediate Metals

This law is stated in one of several ways, and although the statements may appear quite different, they are really equivalent with the exception that the law of the homogeneous circuit is included in some of the statements. One statement of this law is: *The algebraic sum of the thermoelectromotive forces in a circuit composed of any number of dissimilar metals is zero, if all of the circuit is at a uniform temperature.* This law follows as a direct consequence of the second law of thermodynamics, because if the sum of the thermoelectromotive forces in such a circuit were not zero, a current would flow in the circuit. If a current should flow in the circuit, some parts of it would be heated and other parts cooled, which would mean that heat was being transferred from a lower to a higher temperature without the application of external work. Such a process is a contradiction of the second law of thermodynamics and therefore we conclude that the algebraic sum of the thermoelectromotive forces is zero in such a circuit.

Combining this law with that for a homogeneous circuit, it is seen that in any circuit, if the individual metals between junctions are homogeneous, the sum of the thermal electromotive forces will be zero provided only that the junctions of the metals are all at the same temperature.

Another way of stating the law of intermediate metals is:

If in any circuit of solid conductors the temperature is uniform from any point P through all the conducting matter to a point Q, the algebraic sum of the thermoelectromotive forces in the entire circuit is totally independent of this intermediate matter and is the same as if P and Q were put in contact. Thus it is seen that a device for measuring the thermoelectromotive force may be introduced into a circuit at any point without altering the resultant e.m.f. provided that the junctions which are added to the circuit by introducing the device are all at the same temperature. It is also obvious that the e.m.f. in a thermoelectric circuit is independent of the method employed in

forming the junction as long as all of the junction is at a uniform temperature, and the two wires make good electrical contact at the junction, such as is obtained by welding or soldering.

A third way of stating the law of intermediate metals is:

The thermal e.m.f. generated by any thermocouple AB with its junctions at any two temperatures T_1 and T_2, is the algebraic sum of the e.m.f. of a thermocouple composed of A and any metal C and that of one composed of C and B, both with their junctions at T_1 and T_2 or $E_{AB}=E_{AC}+E_{CB}$.

From this statement of the law it is seen that if the thermal e.m.f. of each of the metals A, B, C, D, etc. against some reference metal is known, then the e.m.f. of any combination of these metals can be obtained by taking the algebraic differences of the e.m.f.'s of each of the metals against the reference metal. Investigators tabulating thermoelectric data have employed various reference metals such as mercury, lead, copper, and platinum. At present it is customary to use platinum because of its high melting point, stability, reproducibility, and freedom from transformation points.

3. Law of Successive or Intermediate Temperatures

The thermal e.m.f. developed by any thermocouple of homogeneous metals with its junctions at any two temperatures T_1 and T_3 is the algebraic sum of the e.m.f. of the thermocouple with one junction at T_1 and the other at any other temperature T_2 and the e.m.f. of the same thermocouple with its junctions at T_2 and T_3. Considering the thermocouple as a reversible heat engine and applying the laws of thermodynamics to the circuit, it will be shown in the next section that

$$E=\int_{T_1}^{T_3}\phi dT,$$

from which it follows that

$$E=\int_{T_1}^{T_2}\phi dT+\int_{T_2}^{T_3}\phi dT.$$

This law is frequently invoked in the calibration of thermocouples and in the use of thermocouples for measuring temperatures. It will be discussed in detail in Section IV.

The above are all the fundamental laws required in the measurement of temperatures with thermocouples. They may be and frequently are combined and stated as follows: The algebraic sum of the thermoelectromotive forces generated in any given circuit containing any number of dissimilar homogeneous metals is a function only of the temperatures of the junctions. It is seen then that if all but one of the junctions of such a given circuit are maintained at some constant reference temperature, the e.m.f. developed in the circuit is a function of the temperature of that junction only. Therefore, by the proper calibration of such a device, it may be used to measure temperatures.

It should be pointed out here that none of the fundamental laws of thermoelectric circuits which make it possible to utilize thermocouples in the measurement of temperatures, depends upon any assumption whatever regarding the mechanism of interconversion of heat and electrical energy, the location of the e.m.f.'s in the circuit, or the manner in which the e.m.f. varies with temperature.

III. Historical Investigation and Theory

Although a knowledge of the location of the electromotive forces in a thermoelectric circuit and the mechanism by which heat is converted into electrical energy, is not required in order to measure temperatures with thermocouples, any information available on these subjects may be used advantageously in studying the characteristics of thermocouples and their behavior during use. Various theoretical and experimental investigations of thermoelectric circuits give us the location of the electromotive forces in such a circuit, and the relation between these electromotive forces, but they have not yielded a satisfactory explanation of the mechanism by which heat is converted into electrical energy or of the manner in which the electromotive force varies with temperature, except empirical relations.

In 1834 Peltier[3] found that when a current is passed across the junction of two dissimilar metals in one direction heat is absorbed and the junction cooled, and that when the current is

passed in the opposite direction the junction is heated. Peltier and others observed that for a given current the rate of absorption or liberation of heat at the junction of two dissimilar metals depends upon the thermoelectric power (dE/dt) of the two metals and is independent of the form and dimensions of the metals at the junction. In 1853 Quintus Icilius[4] showed that the rate at which heat is absorbed or generated at a junction of two dissimilar metals is proportional to the current. This heating or cooling effect discovered by Peltier should not be confused with the Joule heating effect which, being proportional to the electrical resistance and to the square of the current, depends upon the dimensions of the conductor and does not change sign when the current is reversed.

Inasmuch as heat is absorbed when a current flows up a potential gradient and heat generated when the current flows down a potential gradient, the heating or cooling effect at a junction of two dissimilar metals (being proportional to the current) is evidence that the junction is the seat of an electromotive force. If we let P be the rate at which heat (in joules per second or in watts) is generated or absorbed when a current of one ampere flows across a junction, then P is the Peltier coefficient of the junction (in watts per ampere) or more simply the Peltier e.m.f. (in volts). The direction and magnitude of this e.m.f. depend upon the metals which form the junctions and upon the temperature.

In 1851, W. Thomson[5] (later Lord Kelvin) concluded from thermodynamic reasoning and the then known characteristics of thermocouples, that the reversible absorption of heat at the junctions of dissimilar metals was not the only reversible heat effect in a thermoelectric circuit. In brief he reasoned as follows:

(1) Assuming that the Peltier e.m.f.'s represent the only reversible effects in a simple thermoelectric circuit, the resultant e.m.f. E in the circuit is given by

$$E=P_2-P_1, \tag{1}$$

where P_1 is the Peltier e.m.f. of the junction which is at temperature T_1 and P_2 is the Peltier e.m.f. of the junction which is at temperature T_2.

(2) Neglecting the effect of thermal conduction (an irreversible process) and considering the thermocouple as a reversible heat engine with a source at the temperature T_2 in degrees Kelvin and a sink at the temperature T_1, we have as a consequence of the second law of thermodynamics

$$P_2/T_2-P_1/T_1=0 \tag{2}$$

or

$$(P_2-P_1)/P_1=(T_2-T_1)/T_1, \tag{3}$$

which combined with (1) gives

$$E=P_1(T_2-T_1)/T_1. \tag{4}$$

It would follow therefore that if one junction were maintained at a constant temperature T_1, P_1 would be constant, and the e.m.f. E would be proportional to (T_2-T_1). It had been definitely shown by a number of investigators that E was not proportional to (T_2-T_1). Thomson therefore concluded that the Peltier effects were not the only reversible heat effects in such a circuit and that there must be a reversible absorption of heat due to the flow of current through that part of the conductors in which there is a temperature gradient.

In 1854 Thomson[6] succeeded in showing experimentally that in certain homogeneous metals, heat is absorbed when an electric current flows from colder to hotter parts of the metal and heat is generated when the current flows from the hotter to colder parts. In certain other metals the opposite of this effect occurs, that is, heat is absorbed when an electric current flows from the hotter to colder parts, and in still other metals, the effect is too small to be detected by the methods used. This heating or cooling effect, called the Thomson effect, being reversible and occurring only where there is a temperature gradient in a metal, is entirely distinct from the irreversible Joule heating.

The reversible absorption of heat in a homogeneous conductor has the same effect as if an electromotive force existed in the temperature gradient. The direction and magnitude of this e.m.f. between any two points depend upon the metal, the temperature, and the temperature difference between the two points. If in any metal we let σ equal the rate at which heat is absorbed or generated per unit difference of temperature when a current of one ampere flows, then the total e.m.f. between any two points at

temperatures T_1 and T_2 is given by

$$\int_{T_1}^{T_2} \sigma dT.$$

In a simple thermoelectric circuit of two metals A and B, Fig. 2, there exist then four separate and distinct electromotive forces, the Peltier e.m.f.'s at the two junctions and the Thomson e.m.f.'s along that part of each wire which lies in the temperature gradient. The only e.m.f. that can be measured as such in this circuit is the resultant e.m.f. The identity of the individual e.m.f.'s can only be established by observations

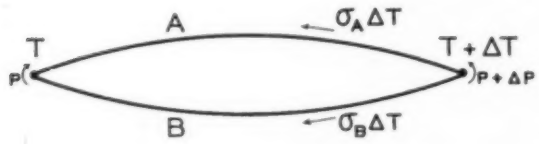


FIG. 2. The location of the electromotive forces in a thermoelectric circuit.

of the reversible heat effects. The Thomson e.m.f. will be considered positive if heat is generated when the current flows from the hotter to colder parts of the conductor and negative if the reverse occurs.

Thomson took into consideration the reversible heat effects in the temperature gradient of the conductors, (Thomson effects), as well as those at the junctions, (Peltier effects), and applied the laws of thermodynamics to the thermoelectric circuit. A complete discussion of this application together with the hypothesis involved is given in the original paper by Thomson.[7]

Consider a simple thermoelectric circuit of two metals A and B, Fig. 2 and let P and $P+\Delta P$ be the Peltier e.m.f.'s of the junctions at temperature T and $T+\Delta T$ in degrees Kelvin, respectively, and let σ_A and σ_B be the Thomson e.m.f.'s per degree along conductors A and B, respectively. Let the metals and temperatures be such that the e.m.f.'s are in the directions indicated by the arrows. The resultant e.m.f. ΔE in the circuit is given by

$$\Delta E = P + \Delta P - P + \sigma_A \Delta T - \sigma_B \Delta T, \quad (5)$$

$$\Delta E = \Delta P + (\sigma_A - \sigma_B)\Delta T, \quad (6)$$

or in the limit

$$dE/dT = dP/dT + (\sigma_A - \sigma_B). \quad (7)$$

By virtue of the second law of thermodynamics $\Sigma Q/T = 0$, for a reversible process. If then we regard the thermocouple as a reversible heat engine and pass a unit charge of electricity q around the circuit, we obtain by considering only the reversible effects*

$$\frac{q(P+\Delta P)}{T+\Delta T} - \frac{qP}{T} + \frac{q\sigma_A \Delta T}{T+\frac{\Delta T}{2}} - \frac{q\sigma_B \Delta T}{T+\frac{\Delta T}{2}} = 0, \quad (8)$$

* The following quotations are from the paper by W. Thomson.

"...The following proposition is therefore assumed as a fundamental hypothesis in the Theory at present laid before the Royal Society.

"The electro-motive forces produced by inequalities of temperature in a circuit of different metals, and the thermal effects of electric currents circulating in it, are subject to the laws which would follow from the general principles of the dynamical theory of heat if there were no conduction of heat from one part of the circuit to another.

"In adopting this hypothesis, it must be distinctly understood that it is only a hypothesis, and that, however probable it may appear, experimental evidence in the special phenomena of thermo-electricity is quite necessary to prove it. Not only are the conditions prescribed in the second Law of the Dynamical Theory not completely fulfilled, but the part of the agency which does fulfill them is in all known circumstances of thermo-electric currents excessively small in proportion to the agency inseparably accompanying it and essentially violating those conditions. Thus, if the current be of the full strength which the thermal electromotor alone can sustain against the resistance in the circuit, the whole mechanical energy of the thermo-electric action is at once spent in generating heat in the conductor;—an essentially irreversible process. The whole thermal agency immediately concerned in the current, even in this case when the current is at the strongest, is (from all we know of the magnitude of the thermo-electric force and absorptions and evolutions of heat) probably very small in comparison with the transference of heat from hot to cold by ordinary conduction through the metal of the circuit. . . . It is true, we may, as has been shown above, diminish without limit the waste of energy by frictional generation of heat in the circuit, by using an engine to do work and react against the thermal electromotive force; but as we have also seen, this can only be done by keeping the strength of the current very small compared with what it would be if allowed to waste all the energy of the electromotive force on the frictional generation of heat; and it therefore requires a very slow use of the thermo-electric action. At the same time, it does not in any degree restrain the dissipation of energy by conduction, which is always going on, and which will therefore bear an even much greater proportion to the thermal agency electrically spent than in the case in which the latter was supposed to be unrestrained by the operation of the engine. By far the greater part of the heat taken in at all, then, in any thermo-electric arrangement, is essentially dissipated, and there would be no violation of the great natural law expressed in Carnot's principle, if the small part of the whole action, which is reversible, gave different, even an enormously different, and either a greater or a less, proportion of heat converted into work to heat taken in, than that law requires in all completely reversible processes. . . ."

which may be written

$$\Delta\left(\frac{P}{T}\right)+\frac{(\sigma_A-\sigma_B)\Delta T}{T+\frac{\Delta T}{2}}=0, \tag{9}$$

or in the limit

$$\frac{d}{dT}\left(\frac{P}{T}\right)+\frac{1}{T}(\sigma_A-\sigma_B)=0 \tag{10}$$

or

$$\sigma_A-\sigma_B=P/T-dP/dT. \tag{11}$$

Eliminating $(\sigma_A-\sigma_B)$ between (7) and (11) we have

$$P=TdE/dT. \tag{12}$$

Substituting (12) in (10) we have

$$(\sigma_A-\sigma_B)=Td^2E/dT^2. \tag{13}$$

From (12) it is seen that

$$E=\int_{T'}^{T}\frac{P}{T}dT=\int_{T'}^{T}\phi dT, \tag{14}$$

which is the expression referred to earlier.

The Peltier e.m.f. at the junction of any two dissimilar metals at any temperature can be calculated from Eq. (12) and measurements of the variation of the thermal e.m.f. with temperature. The magnitude of the e.m.f. existing at the junction of two dissimilar metals ranges from 0 to about 0.1 volt for the metals generally used in temperature measurements.

Although the thermoelectric theory as developed above does not enable us to determine directly the magnitude of the Thomson coefficient in any individual metal, the difference between the Thomson coefficients in two metals can be calculated from Eq. (13) and measurements of the variation in thermal e.m.f. with temperature. Various types of experiments indicate that the Thomson effect in lead is extremely small, if not zero, at ordinary atmospheric temperatures. Consequently some information regarding the magnitude of the Thomson coefficients in other metals at these temperatures can be determined if it is assumed that this coefficient is zero for lead. On this basis it is found that the Thomson coefficient at 0°C in microvolts per °C is −9 for platinum, −8 for iron, +2 for copper, −23 for constantan,† −8 for Alumel,† −2 for 90 platinum −10 rhodium,† and +9 for Chromel-P.†

In order to justify the assumption involved in the application of the second law of thermodynamics, it is necessary and sufficient to verify experimentally the relation

$$P=TdE/dT \tag{12}$$

or

$$\sigma_A-\sigma_B=Td^2E/dT^2. \tag{13}$$

Inasmuch as the individual e.m.f.'s cannot be measured as such, we must depend upon calorimetric measurements of the heating and cooling effects. In order to measure these small reversible effects, it is necessary to separate them from the much larger irreversible Joule heating and the thermal conduction which take place in any experiment of this nature. Practically all of the experimental work on this subject has been on the relation given by Eq. (12) because the reversible heating effects involved in it are in general much larger and more localized than those in Eq. (13).

The most carefully conducted experiments particularly those of Edlund,[8] Jahn,[9] Caswell,[10] and Borelius[11] indicate that the above relations hold within the accuracy of the measurements, about 5 to 10 percent. As far as we know, there is no evidence available which would indicate that the above relations are not exact.

We cannot integrate Eq. (12) or (13) and obtain a general relation between E and T, without some information on the manner in which P or σ varies with T. Experiments indicate that P and σ both depend upon T but the manner in which they vary with T has not been established either theoretically or experimentally with any degree of accuracy.

A number of hypotheses have been made as to the manner in which σ varies with the temperature and Eq. (13) then integrated, but in each case it has been found that the type of equation so obtained represents the experimentally determined values of E and T only over limited temperature ranges. Consequently the relation between E and T for any pair of metals must be determined experimentally and corresponding

† Alloys used in the measurement of temperatures.

values given by tables or empirical relations for limited temperature ranges.

Later theories of thermoelectricity may be divided into two general classes: (1) those in which attempts are made to avoid the hypothesis made by Thomson, and (2) those in which the

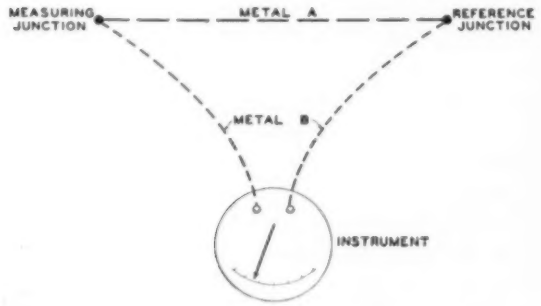


FIG. 3. Simple thermoelectric thermometer.

theory as developed by Thomson is accepted as far as it goes, and attempts are made to derive a reversible mechanism or process for converting heat into electrical energy by the application of the electron theories of metals. The theories in the first general class have added little, if anything, to our knowledge of thermoelectricity. The assumptions involved in most of these appear more objectionable than the one made by Thomson. The relations derived between the quantities involved are either equivalent to or less useful than those derived by Thomson.

The existence of the Peltier and Thomson e.m.f.'s in a thermoelectric circuit may be deduced, qualitatively at least, from the electron theories of metals, but the uncertainties in the quantities involved are so large that we cannot determine whether the theories are in agreement with experimental data or not. The most that can be claimed for the more complete of these theories at the present time, is that they give the order of magnitude of the various effects for certain metals.

IV. Thermoelectric Thermometers

A thermoelectric thermometer is a device for measuring temperatures by utilizing the thermoelectric effects. In its simplest form, it consists of a thermocouple of two dissimilar metals which develop an e.m.f. when the junctions are at different temperatures and an instrument for measuring the e.m.f. developed by the thermocouple, connected together as shown in Fig. 3.

As long as the instrument is at essentially a uniform temperature, all the junctions in the instrument including the terminals, will be at the same temperature, and the resultant thermal e.m.f. developed in the circuit is not modified by including the instrument. If the reference junction is maintained at some reference temperature, such as 0°C, the e.m.f. developed by the thermocouple can be determined as a function of the temperature of the measuring junction. The device can then be used for measuring temperatures. It is not necessary to maintain the reference junction at the same temperature during use as during calibration. However, the temperature of the reference junction in each case must be known. For example, let the curve in Fig. 4 be the relation between the e.m.f. E and temperature t for a particular thermocouple with the reference junction at 0°C. Suppose the device is used to measure some temperature and an e.m.f. E_x is observed when the reference junction is at 30°C. We may add the observed e.m.f. E_x to E_{30} (the e.m.f. given by the thermocouple when one junction is at 0 and the other at 30°C) and obtain from the curve the true temperature t_A of the measuring junction. Certain types of instruments which are used with thermocouples in the manner shown in Fig. 3 are such that they can be adjusted manually for changes in the reference

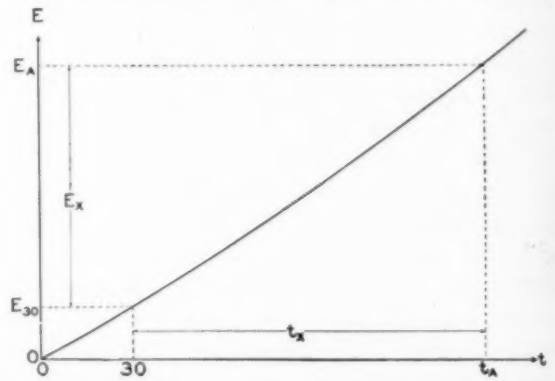


FIG. 4. Illustrating how corrections may be applied for variations in the temperature of the reference junction.

junction temperature and the e.m.f. E_A read directly on the instrument.

Inasmuch as the curves giving the relation between e.m.f. and temperature are not, in

general, straight lines, equal increments of temperature do not correspond to equal increments of e.m.f.

In many cases the thermocouple is connected to the instrument by means of copper leads as shown in Fig. 5.

If the junctions C and C' are maintained at the same temperature, which is usually the case, the circuit shown in Fig. 5 is equivalent to that shown in Fig. 3. If the junctions C and C' are not maintained at the same temperature the resultant thermal e.m.f. in the circuit will depend not only upon the thermocouple materials and the temperature of the measuring junction but also upon the temperatures of these junctions and the thermoelectric properties of copper against each of the individual wires. Such a condition should be and usually is avoided.

Circuits such as shown in Figs. 3 and 5 are used extensively in laboratory work where it is usually convenient to maintain the reference junctions either at 0°C by placing them in a thermos bottle filled with cracked or shaved ice and distilled water or at some other conveniently controlled temperature.

In most commercial installations where it is not convenient to maintain the reference junctions at some constant temperature, each thermocouple wire is connected to the instrument with a lead of essentially the same chemical composition and thermoelectric characteristics as the thermocouple wire, in the manner shown in Fig. 6. This is equivalent to using a thermocouple with the reference junctions at the instrument terminals. Leads which have the same thermoelectric characteristics as the thermocouple wires are

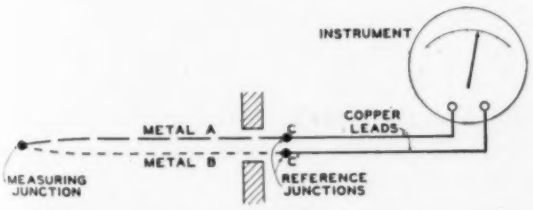


FIG. 5. Diagram for thermoelectric thermometer with copper leads for connecting thermocouple to instrument.

called extension leads. In most installations of this nature the instrument is equipped with an automatic reference junction compensator which automatically changes the indication of the

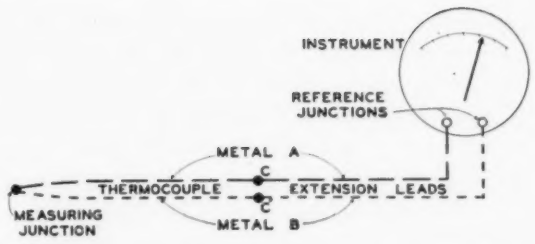


FIG. 6. Thermoelectric thermometer with extension leads.

instrument to compensate for changes in the temperature of the reference junctions, thus eliminating the necessity of measuring or controlling the reference junction temperature. Such automatic devices are usually part of the instrument and in such cases the reference junctions should be located in or at the instrument or at some point which is at the same temperature as the instrument.

In some cases where expensive thermocouple wires are used, extension lead wires of less expensive materials are available which give practically the same temperature-e.m.f. relation as the thermocouple over a limited temperature range, usually 0 to 100°C. Although the combined leads give practically the same temperature-e.m.f. relation as the thermocouple wires, the individual lead wires are not identical thermoelectrically with the thermocouple wires to which they are attached and therefore the two junctions where the leads are attached to the thermocouples (C and C' in Fig. 6) should be kept at the same temperature. This is not necessary in the case of thermocouples where each lead and thermocouple wire to which it is attached are of the same material.

V. Types of Thermocouples

Although a thermal e.m.f. is developed when the junctions of any two dissimilar metals are maintained at different temperatures, only certain combinations of metals have been found suitable for use as thermocouples in the measurement of temperatures. Obviously these thermocouples must be such that:

(1) The thermal e.m.f. increases continuously with increasing temperature over the temperature range in which the thermocouple is to be used.

(2) The thermal e.m.f. is great enough to be measured with a reasonable accuracy.

(3) Their thermoelectric characteristics are not appreciably altered during calibration and use either by internal changes such as recrystallization or by contamination from action of surrounding materials.

(4) They are resistant to any action such as oxidation, corrosion, etc. which destroys the wire.

(5) The melting points of the metals used must be above any temperature at which the thermocouple is to be used.

(6) The metals are reproducible and readily obtainable in uniform quality.

The combinations of metals and alloys extensively used as thermocouples for the measurement of temperatures in this country, are listed in Table I, together with the temperature ranges in which they are generally used and the maximum temperature at which they can be used for short periods. The period of usefulness of a thermocouple depends upon such factors as the temperature, diameter of wires, accuracy required, conditions under which it is used, etc.

There are two types* of platinum to platinum-rhodium thermocouples used in this country, the platinum to 90 platinum-10 rhodium and the platinum to 87 platinum-13 rhodium. These thermocouples develop, at high temperatures, 10 to 14 microvolts per °C as compared to 40 to 55 for the other thermocouples listed in Table I. The platinum to platinum-rhodium thermocouples at temperatures from about 400 to 1600°C being more stable than any other combination of metals, are used (1) for defining the International Temperature Scale from 660°C to the freezing point of gold, 1063°C (only the platinum to 90 platinum-10 rhodium thermocouple is used for this purpose), (2) for very accurate temperature measurements from 400 to 1500°C, and (3) for temperature measurements where the lower melting point materials cannot be used. They are not suitable for temperature measurements below 0°C because the thermoelectric power (dE/dT) is only about 5 microvolts per °C at 0°C and decreases to zero at about −138°C.

The nominal composition of the Chromel-P alloy is 90 percent nickel and 10 percent chromium. Alumel contains approximately 95 percent nickel, with aluminum, silicon, and manganese making up the other 5 percent. Chromel-P-Alumel thermocouples, being more resistant to oxidation than the other base metal thermocouples listed in Table I, are generally more satisfactory than the other base metal thermocouples for temperature measurements from about 650 to 1200°C (1200 to 2200°F). The life of a No. 8 gage (0.128″) Chromel-P-Alumel thermocouple is about 1000 hours in air at about 1150°C (2100°F).

Constantan was originally the name applied to copper-nickel alloys with a very small temperature coefficient of resistance but it now has become a general name which covers a group of alloys containing 60 to 45 percent of copper and 40 to 55 percent of nickel (with or without small percentages of manganese, iron, and carbon) because all the alloys in this range of composition have a more or less negligible temperature coefficient of resistance. Constantan thus includes the alloys made in this country under such trade names as Advance (Ideal), Copel, Copnic, Cupron, etc., most of which contain approximately 55 percent of copper and 45 percent of nickel.

Iron-constantan thermocouples give a slightly higher e.m.f. than the other base metal thermocouples in Table I. They are extensively used at temperatures below about 760°C (1400°F). The life of a No. 8 gage iron-constantan thermocouple is about 1000 hours in air at about 760°C (1400°F).

* Neither one of these thermocouples has any distinct advantage over the other. For several years prior to 1922, there were two classes of supposedly platinum to 90 platinum-10 rhodium thermocouples available which differed in thermoelectric properties by about 10 percent. It was found that one of these contained a large percentage of impurities and that the removal of these impurities eliminated one class of platinum to 90 platinum-10 rhodium thermocouples. However, the scales of a large number of instruments had been graduated to read temperatures directly with these impure thermocouples and in order to provide thermocouples which would give approximately correct readings with these instruments the manufacturers supplied platinum to 87 platinum-13 rhodium thermocouples, which were found to give roughly the same temperature-e.m.f. relation as the "impure 10 percent rhodium thermocouple." New instruments were graduated to read temperatures directly with these new thermocouples and consequently more thermocouples were required. This has gone on and now this type of thermocouple is considered unavoidable.

Copper-constantan thermocouples are generally used for accurate temperature measurements below about 350°C (660°F). They are not suitable for much higher temperatures in air because of the oxidation of the copper.

Combinations of metals other than those listed in Table I are sometimes used for special purposes. As examples, at temperatures above −200°C (−300°F) Chromel-P-constantan gives a thermal e.m.f. per degree somewhat greater than that of any of the thermocouples listed in Table I and is sometimes used when the greater e.m.f. is required. Graphite to silicon carbide has been recommended[12] for temperatures up to 1800°C (3300°F) and for certain applications in steel plants.

VI. Reproducibility of Thermocouples

One of the first requirements of thermoelectric pyrometers for general industrial use is that the scales of the instruments shall be graduated to read temperature directly. Although the indications of the measuring instruments used with thermocouples depend upon the resultant e.m.f. developed in the circuit, the scale of the instrument can be graduated in degrees of temperature by incorporating a definite temperature-e.m.f. relation into the graduation of the scale. The temperature can then be read directly if the temperature-e.m.f. relation of the thermocouple is identical with that incorporated in the scale of the instrument.

All the thermocouples which have the same nominal composition do not give identical relations between e.m.f. and temperature. As a matter of fact, in most cases, two samples of metal which are identical as far as can be determined by chemical methods, are not identical thermoelectrically. This is due in part, to the fact that the thermoelectric properties of a metal depend to some extent upon the physical condition of the metal.

It is not practicable to calibrate the scale of an instrument in accordance with the temperature-e.m.f. relation of a particular thermocouple and to change the scale each time the thermocouple is replaced. Consequently the scales of such instruments are calibrated in accordance with a particular temperature-e.m.f. relation which is considered representative of the type of thermocouple, and new thermocouples are purchased or selected to approximate the particular temperature-e.m.f. relation.

If the temperature-e.m.f. relations of various thermocouples of the same type are not very nearly the same, corrections must be applied to the readings of the indicator, and the corrections will be different for each thermocouple. When several thermocouples are operated with one indicator, and when thermocouples are frequently renewed, the application of these corrections becomes very troublesome. For extreme accuracy it is always necessary to apply such corrections, but for most industrial processes, thermocouples can be manufactured or selected with temperature-e.m.f. relations which are so nearly the same that the corrections become negligibly small.

The accuracy with which the various types of thermocouple materials can be selected and matched to give a particular temperature-e.m.f. relation, depends upon the materials and the degree to which the temperature-e.m.f. relation is characteristic of the materials available. The differences in the temperature-e.m.f. relations of the new platinum to platinum-rhodium thermocouples available in this country rarely exceed 4 to 5°C at temperatures up to 1200°C. Consequently, there is no difficulty in selecting a relation between e.m.f. and temperature which is adequately characteristic of these thermocouples. The temperature-e.m.f. relations used in this

TABLE I. *Types of thermocouples and temperature ranges in which they are used.*

Type of Thermocouple	Usual Temperature Range		Maximum Temperatures	
	°C	°F	°C	°F
Platinum to platinum rhodium	0 to 1450	0 to 2650	1700	3100
Chromel-P to Alumel	−200 to 1200	−300 to 2200	1350	2450
Iron to constantan	−200 to 750	−300 to 1400	1000	1800
Copper to constantan	−200 to 350	−300 to 650	600	1100

country for platinum to platinum-rhodium thermocouples are such that new thermocouples which yield these relations within 2 or 3°C up to 1200°C are readily available.

The differences in the temperature-e.m.f. relations of base metal thermocouples of any one type are so large that the selection of a temperature-e.m.f. relation which might be considered characteristic of the type of thermocouple is difficult and more or less arbitrary. The relations generally used for some of these thermocouples by some manufacturers have been changed from time to time because of differences introduced in the thermoelectric properties of the materials by variations in raw materials and methods of manufacture. However, the relations in use at the present time are such that materials can generally be selected and matched to yield the adopted relations with an accuracy of about ±3°C up to 400°C and to ±¾ percent at higher temperatures. In special cases, materials may be selected to yield the adopted relations within 2 or 3°C for limited temperature ranges.

VII. Temperature-E.M.F. Relations

Corresponding values of temperature and e.m.f. which are considered characteristic of the various types of thermocouples are given in Table II. More detailed tables will be found in the references given in the table. As far as we know the corresponding values given for platinum to 90 platinum-10 rhodium, platinum to 87 platinum-13 rhodium, and Chromel-P-Alumel thermocouples are more or less standard and are the only ones used in this country for these types of thermocouples. The temperature-e.m.f. relation of Chromel-P-Alumel thermocouples has been fairly well controlled because these materials are manufactured primarily with controlled thermoelectric properties for thermocouples by only one company.

The values for iron-constantan headed *A* were determined at the National Bureau of Standards a few years ago as being characteristic of the iron and constantan generally available at that time. The values for iron-constantan headed *B* have been used by certain pyrometer manufacturers for a number of years and presumably are characteristic of the materials available at the time the corresponding values were determined. Owing to the differences in the thermoelectric properties of different lots of iron and constantan, materials must be selected and properly matched in order to obtain a thermocouple which will approximate a selected temperature-e.m.f. relation for this type of thermocouple.

Until recent years copper-constantan thermocouples were used primarily for accurate measurements at temperatures below about 350°C, and in such cases it is customary to calibrate each thermocouple or lot of wire and use an instrument calibrated in millivolts. However, in recent years, there has been an increasing demand for direct reading instruments for use with copper-constantan thermocouples. There are large differences in the temperature-e.m.f. relations of copper-constantan thermocouples and consequently the materials must be selected in order to obtain thermocouples which will yield any specified temperature-e.m.f. relation. No difficulty has been encountered in obtaining thermocouples which will give very closely the temperature-e.m.f. relation in Table II.

VIII. Instruments

Instruments used to measure the e.m.f. developed by thermocouples or to indicate the

TABLE II. *Corresponding values of temperature and e.m.f. for various types of thermocouples.*

Temp. °C	90 Pt-10 Rh to Platinum[1] mv	87 Pt-13 Rh to Platinum[1] mv	Chromel-P to Alumel[2] mv	Iron to Constantan		Copper to Constantan[3] mv
				A[3] mv	*B*[4] mv	
−200			−5.75	−8.27		−5.539
−100			−3.49	−4.82		−3.349
0	0.000	0.000	0.00	0.00	0.00	0.000
+100	0.643	0.646	+4.10	+5.40	+5.28	+4.276
200	1.436	1.464	8.13	10.99	10.78	9.285
300	2.315	2.394	12.21	16.56	16.30	14.859
400	3.250	3.398	16.39	22.07	21.82	20.865
500	4.219	4.454	20.64	27.58	27.39	
600	5.222	5.561	24.90	33.27	33.16	
700	6.260	6.720	29.14	39.30	39.19	
800	7.330	7.927	33.31	45.72	45.48	
900	8.434	9.177	37.36	52.29	51.82	
1000	9.569	10.470	41.31	58.22	58.16	
1100	10.736	11.811	45.14		64.50	
1200	11.924	13.181	48.85			
1300	13.120	14.562	52.41			
1400	14.312	15.940	55.81			
1500	15.498	17.316				
1600	16.674	18.679				
1700	17.841	20.032				

[1] Nat. Bur. Stand. J. Research **10**, 275 (1933), R.P. 530.
[2] Nat. Bur. Stand. J. Research **14**, 239 (1935), R.P. 767.
[3] Nat. Bur. Stand J. Research **20**, 337 (1938), R.P. 1080.
[4] Catalogs. Leeds & Northrup Co. and Brown Instrument Co.
[5] *Pyrometry*, (Symposium published by Am. Inst. Mining Met. Engrs. 1920), p. 165. Int. Crit. Tab. 1, 58 (1926). Nat. Bur. Stand. J. Research **20**, 337 (1938), R.P. 1080.

temperature of the measuring junction of a thermocouple may be divided into two general classes: (1) Those operating upon the galvanometric principle such as ordinary millivoltmeters; and (2) those operating upon the potentiometric principle. At one time there was considerable interest in a class of instruments which operate upon a combination of the galvanometric and potentiometric principles but at the present time there appears to be no place or demand for such instruments.

Millivoltmeters

A millivoltmeter consists of a coil of wire suspended between the poles of a permanent magnet so that the coil is free to move. A pointer is attached to the coil and moves over a scale graduated in millivolts or in degrees. Leads from the thermocouple are connected to the terminals of the coil usually through a series resistance, and the e.m.f. generated in the thermocouple circuit sends a current through the coil, causing it to deflect in the magnetic field. The magnitude of the deflection depends upon the current through the coil which in turn depends on the e.m.f. generated by the thermocouple and the resistance of the circuit.

The current I in the circuit is given by

$$I=E/(R_g+R_x),$$

where E is the resultant e.m.f. in the circuit, R_g the resistance of the millivoltmeter, and R_x the resistance of the thermocouple and leads. The potential difference, E_g, across the terminals of the instrument is given by

$$E_g=\frac{R_g}{R_g+R_x}E.$$

Millivoltmeters are ordinarily calibrated to indicate E correctly when connected to a thermocouple and leads of combined resistance R_x. Any change then in either R_g or R_x causes a change in the indications of the instrument. Inasmuch as instruments are frequently used with more than one thermocouple and inasmuch as R_x varies with the temperature and the amount of the wire heated, it is desirable to make R_g large compared to R_x or at least to variations in R_x. However, this cannot be accomplished in most instances because the design of a millivoltmeter for any particular service is a compromise between sensitivity and ruggedness, which to a large extent determines the resistance. Millivoltmeters

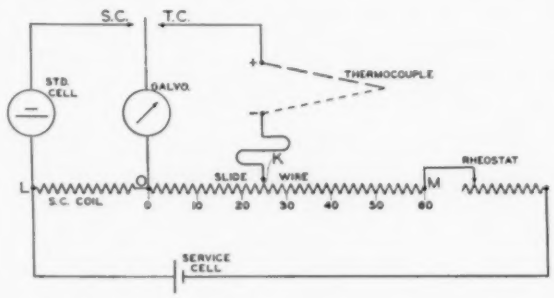


Fig. 7. Diagram of a potentiometer circuit.

with a resistance of much over 600 ohms become extremely delicate and cannot be used in many locations. In order to obtain the ruggedness required it is necessary in some instances to make R_g as low as 12 or 15 ohms. This means that variations in the resistance of the circuit have an appreciable effect upon the indications of the instrument. Owing to these inherent sources of error, millivoltmeters are not very extensively used at the present time.

Potentiometers

The fundamental principle of the potentiometer may be seen by referring to Fig. 7. The current from a service cell which may be a dry cell or a storage cell, passes through the main circuit composed of a series of fixed resistors and can be adjusted by a variable rheostat. The relative values of the fixed resistors and the magnitude of the current determine the range of the instrument. By means of a switch either the standard cell or the thermocouple can be connected to the main circuit and its voltage balanced, through a galvanometer, against an equal voltage drop developed in a portion of the main circuit. The potential drop across the various fixed resistors is made to correspond to definite and reproducible values of voltage by adjusting the current to some standard value.

To standardize the battery current, the switch *S.C.* is closed and the current adjusted until the potential drop across the resistor *LO* is equal to the e.m.f. of the standard cell. The e.m.f. of the

thermocouple can then be determined by closing the *T.C.* switch and moving the contact *K* until the potential drop in the resistors in the main circuit from *O* to *K* is equal to the e.m.f. of the thermocouple. The potential drop from *O* to *K* is read on some suitable scale. The resistors included between *O* and *M* may be made up of fixed coils, a slidewire, or a combination of the two.

The galvanometer has no measuring function but serves solely to indicate zero current in its branch of the circuit. As there is no current through the galvanometer and thermocouple when a balance is obtained, the reading of the potentiometer is independent of the resistance of the thermocouple circuit. However, large changes in this resistance affect the precision of balancing because as the resistance is increased the sensitivity of response of the galvanometer is decreased and the greater is the change in e.m.f. required to produce a perceptible deflection of the galvanometer. It is therefore advisable to keep the resistance of the thermocouple and leads within reasonable limits as determined by the characteristics of the galvanometer.

There are several important advantages in the potentiometer method. The scale is easily made very open, thus permitting precise readings if a suitable galvanometer is used. The accuracy of the potentiometer is in no way dependent upon the constancy of magnets, springs, or jewel bearings, nor upon the level of the instrument. Insofar as temperature measurements with thermocouples are concerned, the greatest advantages are the accuracy and the complete elimination of any error due to ordinary changes in the resistance of the thermocouple and leads. The objections to the potentiometer are its higher initial cost and the fact that, except for automatic instruments, a manual adjustment must be made to obtain a reading. In the recording and controlling potentiometer equipment, however, all the various manipulations may be performed automatically even to the standardizing of the battery current.

Potentiometers are used for practically all laboratory work where the highest accuracy is required. At the present time the large part of the instruments in industrial use operate upon the potentiometric principle.

The scales of millivoltmeters or potentiometers may be calibrated either in millivolts or in degrees of temperature for a particular type of thermocouple. Either type of instrument can be made automatically recording and can be equipped with devices for automatically controlling the temperature of a process or furnace.

Inasmuch as the e.m.f. developed by a thermocouple depends upon the temperature of the reference junctions as well as upon the temperature of the measuring junction, corrections must be made for changes in the reference junction temperature unless they are automatically taken care of by the instrument. If properly calibrated, an ordinary millivoltmeter will indicate the temperature of the measuring junction, when the pointer of the indicator is set to read the reference junction temperature on open circuit. If the reference junction temperature is well controlled, this adjustment may be made conveniently by hand. However, if this junction is subject to frequent temperature changes it is advisable to locate the reference junctions at the instrument and use an instrument which automatically changes the indication to compensate for changes in the reference junction temperature. In the case of millivoltmeters this is accomplished automatically by attaching a properly adjusted bimetallic spring to the control spring of the moving coil. If an instrument is equipped with an automatic reference junction compensator for one type of thermocouple, it should not be used with other types of thermocouples nor should it be used in any case unless the reference junctions are located at the instrument.

Potentiometers for industrial use are usually provided with either a hand-operated or an automatic reference junction compensator. A hand-operated compensator is an adjustable resistor, having a scale graduated in millivolts, which the operator sets to correspond with the observed reference-junction temperature. This operation is equivalent to moving the fixed end of the thermocouple circuit (point 0 Fig. 7) to a point corresponding with reference-junction temperature. For use with any one type of thermocouple the compensator may include a nickel coil which varies in resistance as the temperature changes and thus compensates automatically for

changes in the reference-junction temperature. An instrument so equipped is usually calibrated directly in degrees of temperature. Although it is usually at the instrument, an automatic compensator can be located wherever desired. Lead wires from thermocouple to the compensator location in any case must have the same thermoelectric characteristics as the thermocouple wires.

Instruments calibrated in millivolts are generally used:

(1) When very accurate temperature measurements are to be made with individually calibrated thermocouples.
(2) When used with various types of thermocouples.

Instruments are generally calibrated in degrees of temperature:

(1) When used in industrial plants with only one type of thermocouple.
(2) When the inconvenience of converting millivolt values to temperature is considered more important than the errors introduced by the lack of reproducibility of thermocouples of any one type.

Instruments are ordinarily equipped with manually operated reference junction compensators:

(1) When used with various types of thermocouples.
(2) When the reference junctions are not located at the instrument.

Instruments are ordinarily equipped with automatic reference junction compensators:

(1) When the reference junctions are located at the instrument and subject to considerable variations in temperature.
(2) When the inconvenience of making manual adjustments or arithmetical corrections is considered more important than the errors introduced by using automatic compensators.

IX. Protection Tubes

One of the reasons why the materials listed in Table I have come into common use for thermocouples is that they are reasonably stable thermoelectrically when heated in a clean oxidizing atmosphere. The standards of performance which are generally accepted for the various combinations of thermocouple materials are based upon their performance in air. Although it has not been shown that a reducing atmosphere, in itself, necessarily contaminates or alters the thermoelectric properties of thermocouple materials, it is nevertheless generally observed that exposure of thermocouples to such atmospheres is accompanied by contamination or changes in the chemical composition which seriously alter the thermoelectric properties. In order to obtain the best performance of thermocouples, it appears necessary to maintain them in an atmosphere having essentially the same composition as air. Consequently the selection of a proper protection tube, which will protect the thermocouple from vapors, fumes, or furnace gases, is sometimes as important as the selection of the thermocouple materials.

Changes in thermoelectric characteristics result from causes such as the following.

(1) Metals (solid, liquid, or vapor) coming into contact with the thermocouple materials and altering their chemical composition.

(2) Furnace gases and fumes coming into contact with the thermocouple materials. Sulphur and sulphur compounds are particularly deleterious.

(3) Materials normally stable in an oxidizing atmosphere coming into contact with the thermocouples in a reducing atmosphere. One common cause of contamination, which is serious in the case of rare metal thermocouples, is the reduction of silica (usually present in insulating and ceramic protection tubes) to silicon which readily combines with the thermocouple materials.

(4) Preferential oxidation and reduction of base metal alloys exposed alternately to oxidizing and reducing atmospheres. This results in a gradual change in chemical composition, because all the elements which comprise an alloy are not oxidized and reduced at the same rates under all conditions.

Many types of protection tubes are required in order to meet all needs. In many cases, the conditions under which thermocouples are used are such that two tubes are required to provide the desired protection. For instance, a primary

tube of porcelain or fused silica may be placed inside a secondary tube of metal, silicon carbide, or fire clay. The primary tube of low volatility is intended to provide imperviousness to gases at high temperatures, and the secondary tube to provide resistance to thermal and mechanical shock and to corrosion.

In thus providing protection for the thermocouple, however, one should not lose sight of the fact that a thermocouple can perform its function only when the conditions of heat transfer are such that the measuring junction attains or at least approaches the temperature to be measured. When a tube of large cross section or more than one tube is used, particularly if the tubes have a high thermal conductance, it should be carefully considered whether the depth of immersion is sufficient to insure that the temperature of the thermocouple junction is reasonably close to the temperature to be measured. Short thick-walled tubes may cool the junction so much that the indications are comparatively worthless.

Platinum to platinum-rhodium thermocouples are particularly susceptible to contamination and should be protected by ceramic tubes which are impervious to gases and vapors at all operating temperatures. Metal protection tubes usually provide sufficient protection for base metal thermocouples. The oxide coatings on the thermocouple wires are fairly effective in protecting the wires from contamination by metallic vapors. Metal tubes which provide sufficient protection in an oxidizing atmosphere may be entirely unsatisfactory if large amounts of furnace gases are present. In some installations it has been found advisable to ventilate the interior of the protection tube with a slow stream of air in order to minimize the deleterious effects of furnace gases.

The primary ceramic tubes which meet most requirements of stability and imperviousness to gases are: highly refractory porcelain, sometimes called "Sillimanite" or "Mullite" for temperatures up to about 1550°C (2800°F), fused silica for temperatures up to about 1050°C (1900°F) in an oxidizing atmosphere, and Pyrex glass for temperatures up to about 600°C (1100°F).

The secondary or metal tube most suitable for a particular application depends to a large extent upon the type of corrosion encountered. Nickel-chromium-iron tubes are particularly useful in oxidizing atmospheres, chromium-iron tubes in atmospheres containing sulphur, and nickel or iron tubes in hot caustic and molten metal baths. The temperature limits given in Table III for the various types of tubes are those which will, in general, result in a reasonably long life. The tubes may be used at higher temperatures than those given but higher operating temperatures will result in a shorter life.

Fire clay, silicon-carbide, and graphite meet certain requirements of secondary tubes at temperatures above the useful limits of metal tubes. Numerous other types of tubes have been developed for specific purposes. Recommendations regarding tubes for any particular purpose may be obtained from pyrometer manufacturers.

X. Calibration of Thermocouples

Various methods used for calibrating thermocouples and of testing thermocouple materials and the precautions which must be observed in order to attain various degrees of accuracy are given in a separate paper, which is essentially the same text as the paper entitled "Methods of testing thermocouples and thermocouple materials" published originally in the *Journal of Research of the National Bureau of Standards*.[13] The numerical values in the original text have been brought into agreement with later published data.

XI. Measurement of Temperatures

The measurement of the temperature of any particular object or space is in many cases a problem in itself, even after a suitable thermocouple has been selected and calibrated. The methods employed in many instances are described elsewhere in this symposium. However, there are certain fundamentals that must be observed in any case.

The temperature indicated by a thermocouple is that of its measuring junction, but usually this is of no interest in itself. The accuracy obtained in measuring the temperature of any object or space usually depends upon how closely the junction of the thermocouple can be brought to the same temperature as that of the object or space, or to some temperature which is definitely related to that of the object or space.

TABLE III. *Recommended maximum operating temperature of metal protection tubes.*

TYPE OF TUBE	RECOMMENDED MAXIMUM TEMPERATURE	
	°C	°F
Seamless steel	550	1000
Wrought iron	700	1300
Cast iron	700	1300
Calorized wrought iron	800	1500
14 percent chromium iron	800	1500
28 percent chromium iron	1100	2000
18 (Cr)-8 (Ni)-stainless steel	850	1600
32 Ni-20 Cr-48 Fe	1100	2000
62 Ni-13 Cr-25 Fe	1150	2100
Nickel	1100	2000

If under steady conditions there is a net exchange of heat between the thermocouple junction and an object, then there is a difference in temperature between the two. The magnitude of this difference in temperature depends upon the rate of heat transfer and the thermal resistance between the junction and the object. The idea then is to bring the thermocouple junction into as good thermal contact as possible with the object and to insulate the junction as well as possible against the transfer of heat to or from other objects or spaces. Greater precautions are obviously necessary in accurate measurements than in rough ones.

As an illustration, suppose we desire to measure the temperature of a metal plate which is heated from within by some means. The bare thermocouple junction is brought into contact with the metal plate. The junction will receive some heat from the plate by thermal conduction and probably a smaller amount, by radiation and convection. The junction will lose heat by conduction along the thermocouple wires, and by convection, conduction, and radiation to the surroundings. Obviously the junction will be at a lower temperature than the plate. However, this difference in temperature can be reduced by the following.

(A) By improving the thermal contact. (1) By flattening the junction to obtain a larger area of contact or better still (2) by soldering, brazing, or welding the junction to the plate.

(B) By reducing the heat loss from the junction. (1) By keeping the wires close to the plate for some distance so as to reduce the temperature gradient in the wires near the junction, and/or (2) by raising the temperature of the space immediately surrounding the junction (a) by insulating the junction from that space or (b) by utilizing an auxiliary source of heat as is done in the compensated contact thermometer.[14,15]

The thermocouple junction may be at either a higher or lower temperature than the object depending upon the direction of the net heat transfer. The use of thermocouple protection tubes usually makes it more difficult to bring the thermocouple junction to nearly the same temperature as that of an object, because of the additional thermal resistance introduced between the junction and object and the additional transfer of heat along the protection tubes. For example, the junction of a thermocouple may be brought within a few hundredths of a degree of the temperature of a liquid by immersing the bare wires in the liquid for a distance of 5 to 10 diameters of the wire, whereas if a protection tube is used with the thermocouple it will be necessary to immerse the junction 5 to 10 diameters of the protection tube to obtain the same degree of accuracy. In most applications, the best that can be done is to bring the thermocouple junction and object as close together as possible and immerse the thermocouple as far as practicable in the heated medium.

In the measurement of certain temperatures, particularly those of small objects and materials of low thermal conductivity, consideration must be given to the possibility that the temperature to be measured may be altered by the introduction of the temperature measuring device.

In the measurement of temperatures varying with time, heat capacity of thermocouples and protecting tubes as well as thermal contacts are involved. If the temperature is rising, the temperature of the junction itself will at any instant be lower than that of the surroundings. The reverse will be true if the temperature is falling. This is referred to as thermal lag. By appropriate auxiliary measurements, however, it is usually possible to determine the lag[16] under the particular conditions of use, and apply corrections to the thermocouple readings.

XII. Installations

The cost of pyrometer equipment is great enough to warrant installing it, not only so that the desired temperature can be measured with

the required accuracy but also in such a manner as to protect the equipment, as far as practicable, from changes and deterioration. The installation of simple pyrometer equipment for more or less temporary service in an air-conditioned laboratory, far removed from the vibrations set up by heavy equipment such as trip hammers, rolling mills, etc., is a comparatively simple matter. However, in the large installations required in many industrial plants, every precaution should be taken to protect the thermocouple, wiring, and instruments from the various deleterious conditions which may seriously affect their accuracy and life.

1. General Precautions

The installation of extensive thermocouple equipment requires the services of competent electricians. Just as much attention, if not more, should be given to the wiring, switches, switchboards, etc., as is given in the case of ordinary power installations. Proper fixtures should be used to mount the thermocouples in the furnaces. Lead wires should have a weatherproof covering and should be run in a metal conduit except possibly for a short length of flexible cable at the ends of the conduit. The conduit should be grounded to prevent leakage from power installations or lighting circuits. All joints in the lead wires should be soldered and taped. When indicators or recorders of low resistance are employed, it is of the greatest importance to have a well-constructed electrical installation to insure a constant line resistance. Since instruments of low resistance are usually calibrated for a low line resistance of definite value, special attention must be given to contact resistances at switches. Frequently switches rated at 100 amperes are required, although the actual thermoelectric current is only a few milliamperes. If the indicator is of high resistance, or operates upon the potentiometric principle, the factor of very low line resistance is not of great importance, but the wiring should be well installed, to avoid large changes in the resistance. Stationary indicating and recording instruments usually should be mounted upon switchboards, with suitable selective or commutating switches when several thermocouples are to be used with one indicator. When the junction between the thermocouple

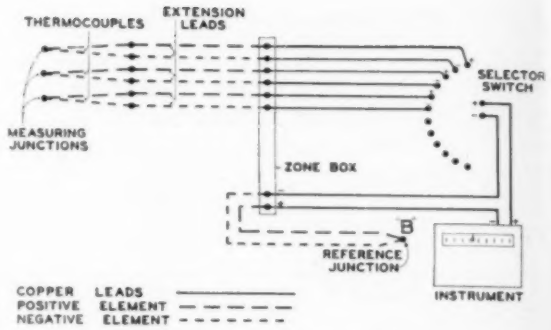


Fig. 8. Connections between several thermocouples and a distant instrument.

and leads is exposed to severe conditions, rain, etc., as in outside kilns, a weatherproof terminal head should be used. This consists of an outside casing which fits over both binding posts. The cover may be tapped for conduit wiring or provided with a packing gland or stuffing box if a length of flexible cable is used between the thermocouple and the conduit.

The indicator or recorder should be conveniently located. If the instrument is desired especially for the use of the operator of a furnace, it should be placed where it is readily visible. It should be mounted where vibration and excessive dirt and dust will not injure delicate parts of the mechanism. In almost all industrial installations an outside protecting case is required to prevent dust from filtering through the case of the indicator. Special devices are employed to damp out vibration when this is serious, as in the neighborhood of a trip hammer or rolling mill. Frequently the instruments are suspended on "vibration-proof mountings."

2. Location of Thermocouples

The proper location of the thermocouple in a furnace depends upon the particular process and the use to which the furnace is put. The primary consideration is to locate the measuring junction so that it acquires the temperature which it is desired to measure. This requires taking into consideration the thermal lag and heat transfer to and from the thermocouple junction. Both of these factors are materially affected by protection tubes. A secondary consideration, however, is to locate the thermocouple where the lead wires may be conveniently located. The space between

the protecting tube and the furnace wall should be plugged with refractory cement, so that hot air cannot strike through the hole onto the terminals of the thermocouple, nor cold air be drawn in, thus cooling the measuring junction of the thermocouple.

3. Common Return

The use of a common return wire for a multiple installation is in general unsatisfactory. When grounds or short circuits occur at any point between the measuring junctions and the instrument—for example, between the common return and the other lead wire of one thermocouple—all the thermocouples on the common return have, in addition to their own e.m.f., an impressed potential drop due to the current flowing in the shorted thermocouple. This may cause a large error in the reading of every thermocouple in the system. With the common return, leakage from a power installation affects the readings of every thermocouple connected to the return and a leakage through a high resistance may alter the readings of every thermocouple by the same amount so that the presence of such leaks is not always readily detected. It is also possible by leakage from different thermocouples to the ground to obtain very erratic and erroneous readings when the common return is employed. The insulation resistance of materials becomes very low at high temperatures making it difficult to insulate the various thermocouple wires from one another and from the furnace parts, even when individual returns are used. Base-metal thermocouples are frequently constructed with the measuring junction welded to the end of the metal protecting tube in order to reduce thermal lag. Even when the thermocouple is not welded at this point, the measuring junction usually touches the protecting tube and is in good electrical contact with it. If a common return is used when the thermocouples are mounted in this way, any electrical connection or leakage between the metal protecting tubes (through the furnace structure, etc.) will produce serious errors. However, if individual returns are used, the metal protecting tubes need not be insulated from one another. The troubles ordinarily encountered with common return installations are sufficient to warrant the extra cost of the wire required to install individual thermocouple circuits.

4. Use of a Zone Box

Extension lead wires are rather costly and should not be employed extravagantly. Also the use of long lengths of extension leads increases the line resistance, since the resistivity of the lead materials is much higher than that of copper.

For an installation in which several thermocouples are connected through a selector switch to an instrument located at some distance from a furnace, a wiring scheme similar to that shown in Fig. 8 may be very useful in saving extension lead wire and consequently in reducing the cost and resistance of the line. The common reference junction "*B*" for each thermocouple can be located at any conveniently controlled point or at the instrument if the latter is equipped with an automatic reference junction compensator by running only one pair of extension leads from the zone box to the controlled point or the instrument. A zone box is a box or zone of uniform temperature which need not be measured or maintained constant. It should be pointed out that although a common reference junction is used for all the thermocouples, the system is not subject to any of the objections which have been raised against the use of a common return.

5. Thermocouples Purposely Insufficiently Immersed

In many processes a furnace is operated at such a high temperature that a thermocouple or protecting tube cannot withstand the severe conditions inside the furnace. In this case the thermocouple may be advantageously inserted only part way through the furnace wall, or flush with the inner wall of the furnace. The temperatures indicated by thermocouples installed in this manner are always lower than those of the furnace interior, but they may bear a fairly definite relationship to the temperature of the furnace, and hence the method may be satisfactory for temperature control and reproduction of furnace conditions from day to day.

6. Measurement of Average Temperature

It is frequently desirable to measure "the average temperature" of an object or a heated

space by using thermocouples. No discussion of what is meant by the average temperature of an object or space or why anyone would be interested in measuring any such average will be given here. The average temperature that can be measured with thermocouples is only a mean of the temperatures of the measuring junctions of a number of thermocouples. This average may or may not be a close approximation to the average temperature which one desires to measure, depending upon such factors as the temperature distribution, the number and location of the thermocouples, etc.

If the measuring junctions of a number of thermocouples are placed in thermal contact with an object or located in a heated space, the average temperature of the junctions may be obtained by any one of three methods: (1) by reading the thermocouples individually and averaging the readings; (2) by connecting them in series and reading the total e.m.f.; or (3) by making all the thermocouples of equal resistance and connecting them in parallel so that the average e.m.f. is read directly. Although each of these methods has certain practical advantages over the others, they are all equivalent in that one is no more accurate than the others and that the same average temperature (that of the junctions) is measured in each case. In the following discussion, it will be assumed that the temperature-e.m.f. relations of all the thermocouples used in any one case are identical and that any correction or compensation required for the reference junctions is properly cared for.

The important advantages of taking readings of the individual thermocouples are that (1) one obtains not only the average temperature but also some idea of the temperature distribution, (2) the thermocouple junctions may be placed in contact with or welded to metal objects, thus insuring good thermal contact, and (3) the failure of any individual thermocouple is immediately detected. The disadvantage is that several observations must be taken, requiring several instruments if the observations are to be taken simultaneously or considerable time during which the temperatures may change if the observations are to be taken with one instrument.

One may average the values of the e.m.f. of the individual thermocouples and obtain the average temperature from the average e.m.f. or one may average the temperature values obtained for each thermocouple. The average values obtained in these two different ways will not necessarily agree exactly owing to the fact that the e.m.f. of a thermocouple is not a linear function of the temperature. If the temperature gradients in the object or heated space are not very large (less than about 50°C) the difference in the averages obtained in the two different ways is usually insignificant. If the temperature gradients in the object or heated space are so large (several hundreds of degrees) that there is an appreciable difference in the average temperature obtained in the two different ways, the average temperature obtained by using thermocouples located at several selected points probably has no exact significance.

Because values of temperature may be obtained with the individual thermocouples and averaged with this method, it is not necessary to use thermocouples with approximately the same temperature-e.m.f. relation.

The important advantage of connecting the thermocouples in series or in parallel is that only one observation is required to obtain the average e.m.f. of a number of thermocouples. However, such a single observation yields no information regarding the temperature distribution in the object or space. Connecting the thermocouples according to either method requires that the thermocouple wires and measuring junctions be electrically insulated from one another. This makes it difficult under certain conditions to bring the junctions in good thermal contact with an electrically conducting medium.

The objections to connecting a number of thermocouples in series are: (1) The e.m.f. developed by the thermocouples in series may be too great to be measured with the instruments available; (2) A short circuit which might materially reduce the e.m.f. of one of the thermocouples would not be detected by a single observation of the total e.m.f.

It can be shown by applying Kirchhoff's laws, that the potential difference across the terminals of a number of thermocouples of equal resistance connected in parallel is the average of the e.m.f.'s of the individual thermocouples. Inasmuch as the

average e.m.f. is measured directly when the thermocouples are connected in parallel, the e.m.f. can be measured with any instrument that is used for measuring the e.m.f. of a single thermocouple.

It should be pointed out that the temperature indicated when the two individual thermocouple wires are attached to a metal object at two points which may be designated P and Q (so that the electric circuit is completed through the metal), depends upon the thermoelectric power of the metal with respect to the thermocouple wires and is not necessarily the temperature of the metal at any point between P and Q and consequently is not the average temperature of the metal between P and Q except in very special cases. If the metal to which the thermocouple wires are attached is thermoelectrically positive to one element of the thermocouple and negative to the other, the temperature measured will be somewhere between those of P and Q. The thermocouple will indicate a temperature approximately midway between those of P and Q only if the metal is approximately midway between the two thermocouple wires thermoelectrically.

It is readily seen that if the wires of an iron-constantan thermocouple are attached to a piece of iron, the temperature measured will be that where the constantan wire is attached and if they are attached to a piece of constantan the temperature measured will be that where the iron wire is attached.

If the metal to which the thermocouple wires are attached is thermoelectrically positive or negative to both wires of the thermocouple, the value of the temperature indicated will not be between those of P and Q. For example, suppose that the wires of a platinum to 90 platinum-10 rhodium thermocouple are attached to a piece of constantan, and that the temperature of the point where the platinum wire is attached is 700°C and that where the platinum-rhodium is attached is 750°C. Let the reference junctions of the thermocouple be at 0°C. The circuit is equivalent to a 90 platinum-10 rhodium to constantan thermocouple with its junctions at 750° and 0°C in series with a constantan to platinum thermocouple with its junctions at 700° and 0°C. The resultant e.m.f. developed in the circuit will be approximately 9.14 mv which corresponds to 962°C for the platinum to 90 platinum-10 rhodium thermocouple.

XIII. Conclusion

In conclusion the author would like to emphasize that the success attained in the measurement of temperatures with thermocouples depends primarily upon the ability of the observer to bring the junctions of the thermocouples to the desired temperatures and upon the stability of the thermocouple materials. The reader's attention is directed to a number of papers in this symposium which deal with (1) the measurement of temperatures in particular cases, (2) the stability of thermocouples, and (3) the instruments available for use with thermocouples in the measuring, recording, and controlling of temperatures.

XIV. Bibliography

1. T. J. Seebeck, Gilb. Ann. **73**, 115, 430 (1823); Pogg. Ann. **6** 1, 133, and 253 (1826).
2. P. D. Foote and T. R. Harrison, J. Wash. Acad. Sci. **8**, 545 (1918).
3. J. C. A. Peltier, Ann. chim. Phys. 2nd ser. **56**, 371 (1834).
4. Quintus Icilius, Ann. d. Phys. und Chem. Pogg. **89**, 377 (1853).
5. W. Thomson, Proc. Roy. Soc. Edin. December 15, 1851.
6. W. Thomson, Proc. Roy. Soc. Lon. **VII**, May, 1854. Phil. Mag. July, 1854.
7. W. Thomson, Trans. Roy. Soc. Edin. **21**, 123 (1857); Read May 1, 1854.
8. E. Edlund, Pogg, Ann. **140**, 435 (1870); Pogg. Ann. **143**, 404, 534 (1871).
9. H. Jahn, Wied. Ann. **270**, 755 (1888).
10. A. E. Caswell, Phys. Rev. **33**, 379 (1911).
11. G. Borelius, Ann. d. Physik. (4) **52**, 398 (1917); **56**, 388 (1918).
12. G. R. Fitterer, A. I. M. E., Iron & Steel Div. **105**, 290 (1933); A. I. M. E. **20**, 189 (1936).
13. W. F. Roeser and H. T. Wensel, J. Research Nat. Bur. Stand. **14**, 247 (1935), R.P. 768.
14. M. W. Boyer and J. Buss, Ind. & Eng. Chem. **18**, 728 (1926).
15. W. F. Roeser and E. F. Mueller, Bur. Stand. J. Research **5**, 793 (1930), R.P. 231.
16. D. R. Harper, 3rd, Bul. Bur. Stand. **8**, 659 (1912), S185.

Optical Pyrometry*

W. E. FORSYTHE

Lamp Department, General Electric Company, Nela Park, Cleveland, Ohio

AN optical pyrometer is a device for measuring the temperature of a hot body from a determination of either the brightness or the color of the surface of the source studied, generally by eye observations. In this paper the pyrometer and pyrometric methods discussed all apply to temperature determinations from surface brightnesses.

FIG. 1. The first optical pyrometer.

Since the optical pyrometer is not an absolute instrument, a calibration is necessary. This necessitates a known relation between surface brightness and temperature, and of the many sources that might be used, the blackbody is selected. Thus, unless otherwise noted in what follows, the source referred to is the blackbody.

Brightness measurements can not be made accurately by the unaided eye. However, the eye can quite accurately match the brightness of the surface studied with that of another source which necessitates a comparison source.

There have been several methods used in the construction of optical pyrometers to introduce the comparison source. The source may be off to one side and reflected into the line of sight either by a mirror or by a cube as shown in Fig. 2, or it may be built into direct line of sight as shown in Fig. 3, which is a diagram of the disappearing-filament type of optical pyrometer. There are also several methods by which the brightness of the comparison source can be varied so that it can be matched with that of the source being studied. Among these may be mentioned an iris diaphragm between the comparison source and the observing cube or between the source being studied and the cube with the opening varied to bring the images of the two sources to a brightness match. The light from the source being studied and the comparison source may be polarized in planes at right angles to each other and their brightnesses balanced by rotating a Nicol prism in the eyepiece. The use of a variable absorbing screen, properly located, may be used for obtaining a balance, or finally one may follow the principle used in the disappearing-filament optical pyrometer and vary the current through the pyrometer filament to balance it in brightness with the image of the source studied.

The disappearing-filament optical pyrometer is quite similar to a telescope, the main difference being that the pyrometer filament is located

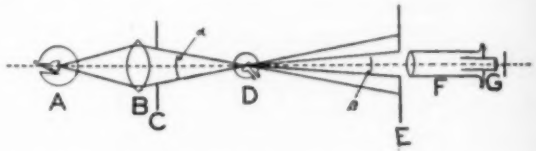


FIG. 2. Arrangement used in one form of Le Chatelier optical pyrometer.

at the focus of the objective lens in place of cross-hairs. In series with the lamp filament is the battery, resistance and ammeter for controlling and measuring the current. Besides its simplicity of construction and use, this pyrometer

* Presented at the Symposium on Temperature, Its Measurement and Control in Science and Industry, November 2–4, 1939, New York, New York.

has two outstanding advantages. In the first place, one can see the object whose temperature is being measured and can thus be sure just what part is being measured. Also, the temperature of objects which, because of their size or their location, would be difficult to measure by any other means, can be easily measured with this pyrometer.

The Optical Pyrometer as a Telescope

Since this type of pyrometer is a telescope, the ordinary precautions concerning the apparent brightness of an image observed through the telescope must be observed.[1] It seems best to have a limiting diaphragm somewhere in the eyepiece rather than to depend upon the eye as the limiting diaphragm. This one limiting diaphragm is sufficient to insure that the brightness of an object observed through the pyrometer does not vary with its distance or magnification as long as this diaphragm is filled with light. However, because of diffraction and reflection at the pyrometer filament and variation from Lambert's cosine law[2] of the intensity of the radiation across a round tungsten filament, the measured temperature of a source may vary with magnification, unless there is a limiting diaphragm between the objective lens and the pyrometer filament. There have been two papers[3] published which deal with the diameter of the pyrometer filament and the relative size of the two cones of light, determined by these two diaphragms, for the best conditions of disappearance of the pyrometer filament. This will not be gone into here, but if the reader is interested, the original papers should be consulted.

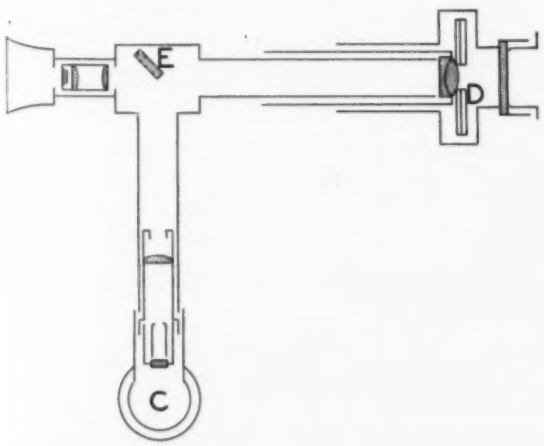


FIG. 3. Schematic arrangement of the disappearing filament optical pyrometer.

The Pyrometer Lamp

The pyrometer lamp should have a very clear glass bulb and, for the most accurate work, should have plane glass windows on both sides.

FIG. 4. Pyrometer lamp.

These windows should not be perpendicular to the axis of the telescope but should be mounted at an angle of about 15 to 20° from perpendicularity so as to avoid reflecting images of the filament into the field of view (Fig. 4).

A tungsten wire makes a very satisfactory pyrometer filament from the standpoint of size, operation, life, and the amount of current required. Such a pyrometer filament, if not used at a temperature higher than that of the melting point of palladium (1828°K), will last almost indefinitely, and any failure will probably be due to accident rather than to any deterioration in the filament.

The vacuum in the bulb should be as good as one can obtain by using mercury vapor pumps, liquid-air traps and high temperature bake-out of the lamp and lighting the filament. A pointer or a small bend in the filament can be used to indicate the exact part used. The filament should be long enough so that the end losses from the two ends will not overlap too much because if they do, the current-temperature relation of the filament may depend upon the ambient temperature for low filament temperatures; that is,

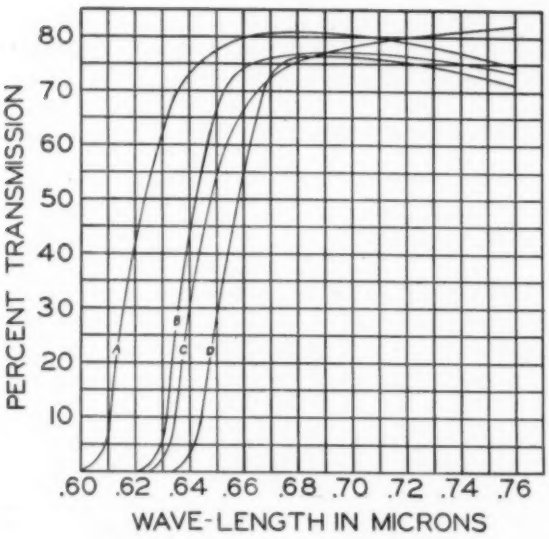


FIG. 5. Spectral transmission of various red glasses. Curve *A*—for Corning high transmission red, marked 150 percent, five mm thick. Curve *B*—for Corning high transmission red, marked 50 percent, 5 mm thick. Curve *C*—for Jena red 4512, 2.93 mm thick. Curve *D*—for Corning high transmission red, marked 28 percent, 6 mm thick.

for temperatures below 700–800°C. A filament 3 cm or more in length will be satisfactory, except for very low filament temperatures, over a wide range of ambient temperatures. A vacuum tungsten lamp will not initially overshoot in brightness for a constant current; nor in an actual pyrometer circuit unless too much of the resistance is in the lamp leads. Thus operated, a filament about 3 cm long and 1 to 2 mils in diameter will be within 1° of its maximum temperature in much less than one second (for temperatures above 800°C) and, if it is already incandescent, it should approximate its final temperature in a shorter time.

How accurately the current through the pyrometer filament must be measured is shown by the following. If the current through the filament is of the order of 0.3 ampere, a change of 0.001 ampere corresponds to a temperature change of about 3°C. Thus, for an accuracy of 1°C, the current will have to be measured to about one part in a thousand. This will, in general, require some sort of a potentiometer device for measuring the current.

Monochromatic Screen

Temperatures can be measured with an optical pyrometer using the total visible spectrum but if this is done, errors are apt to be introduced and observers may differ widely in their readings in the event of a color difference between the comparison source and the source studied. This difficulty can be overcome and a much more accurate brightness match made by using a so-called monochromatic screen in the eyepiece of the pyrometer.

In general a red glass is used as the monochromatic screen because in the first place better red glass screens can be obtained than for other parts of the spectrum and the color change per wave-length interval is less in this part of the spectrum than in any other. When an attempt is made to extend the temperature scale, a rotating sector or an absorbing glass of higher transmission can be used for red radiation than for the green or blue radiation which, of course, is an advantage. Also, heated objects first radiate in the red part of the visible spectrum and thus temperature measurements can be made for a lower temperature using a red screen than for a green or blue screen.

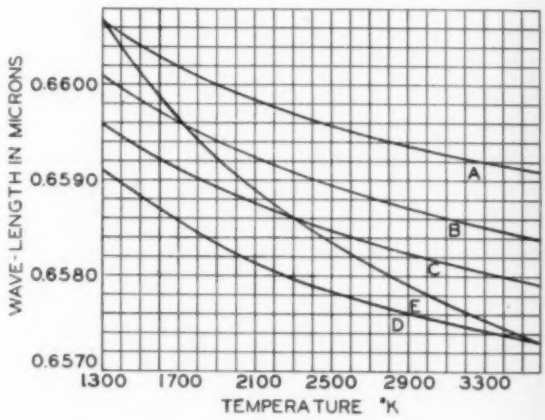


FIG. 6. Effective wave-lengths for Corning red glass. Spectral transmission shown by Curve *B*, Fig. 5. Curve *A*: effective wave-lengths from 1300° to other temperatures. Curve *B*: effective wave-lengths from 1800° to other temperatures. Curve *C*: effective wave-lengths from 2400° to other temperatures. Curve *D*: effective wave-lengths from 3600° to other temperatures. Curve *E*: limiting effective wave-length.

An optical pyrometer can be so calibrated and so used that it is not necessary to know the color characteristics of the monochromatic screen. This requires a standard source for calibration that has the same brightness temperature range

as the pyrometer. Also, if the pyrometer calibrated against a blackbody is used to measure the temperature of nonblackbodies, something must be known concerning the color characteristics of the screen. A monochromator may be used as the eyepiece of an optical pyrometer and thus a very definite wave-length used. This is what has been called a spectropyrometer.[4] However, this is not necessary unless, for some other reason, one wants to use a variety of wave-lengths. Using a good monochromatic screen and what has been defined as its effective wave-length,[5] just as definite results can be obtained as with the best monochromator, yet the instrument is not so complicated and it transmits more light. Also, such results can easily be reduced to a single wave-length if necessary.[6]

The effective wave-length of a monochromatic screen for a definite temperature interval has been defined as the wave-length for which the relative brightness as calculated from Wien's equation for this temperature interval is the same as the ratio of the integral luminosities, for these two temperatures, as measured through the red screen. Expressed in the form of an equation, the following is the definition of the effective wave-length:

$$\frac{\int_0^\infty J(\lambda T_1) t_R K_\lambda d\lambda}{\int_0^\infty J(\lambda T_2) t_R K_\lambda d\lambda} = \left[\frac{J(\lambda T_1)}{J(\lambda T_2)}\right]_{\lambda_e}, \qquad (1)$$

where $J(\lambda T)$ is the spectral distribution of the blackbody (Wien's equation), t_R the spectral transmission of the monochromatic screen; K_λ the luminosity factor and λ_e the effective wave-length.

From this equation the effective wave-length can be calculated using Wien's equation for the energy distribution and the measured transmission of the screen for t_R. The step-by-step integration is sufficiently accurate for this purpose.

Such calculations have been made for a series of temperatures for a selected Corning selenium red glass with the transmission shown by curve *B*, Fig. 5, and the resulting effective wave-length plotted in Fig. 6.

The limiting effective wave-length[7] is the value the effective wave-length approaches as the two temperatures approach each other. The effective wave-length for a definite temperature interval is given quite accurately by the mean of the limiting effective wave-length for the two temperatures. Methods have been outlined for obtaining[8] the effective wave-length of an unknown glass by comparison with a standard glass.

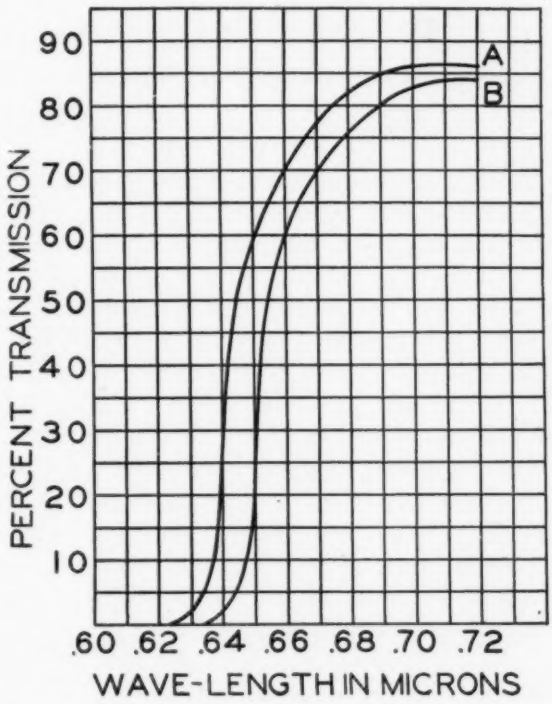


FIG. 7. Spectral transmission of a single thickness of glass *F*-4512; *A* at 20°C; *B* at 80°C.

The transmission of the red glass screen depends upon its temperature.[9] The curves in Fig. 7 show the transmission of one type of red screen at two temperatures. It has been shown[9] that this temperature change of transmission of this red glass will cause no appreciable error for any temperature change that is apt to occur in practice.

Rotating Sectors

It is sometimes necessary to reduce the apparent brightness of a source being studied either for calibration purposes or to measure the temperature of a source that is higher than the pyrometer comparison source can be operated. For work in the laboratory, a rotating sector is very satisfactory for this purpose.

TABLE I. *Errors in temperature measurements due to improper location of sector.*

Position of 2° Sector	Near Lens		Near Pyrometer Lamp	
	Opening of Sector Parallel to Background Filament	Opening of Sector Perpendicular to Background Filament	Opening of Sector Perpendicular to Background Filament	Opening of Sector Perpendicular to Background Filament
Current, in amperes through pyrometer filament for brightness match	0.3332	0.3354	0.3357	0.3357
Apparent relative brightness	0.9390	0.9950	1.0000	1.0000
Temperature of background for these readings in °K	2263	2275	2277	2277

Position of Rotating Sector

If a rotating sector is used with a disappearing-filament optical pyrometer to reduce the apparent intensity of the background, care must be taken as to its location.[10] If the sector is placed near the lens, the image of a small source, or the edges of a large source, may not be clear. This is probably due to diffraction caused by using a part of the lens. This may cause a marked difference in the results of temperature measurements, depending on whether the sector is located near the objective lens or as near as possible to the pyrometer lamp. There is also a difference depending on the relative orientation of the openings in the sector and the source, providing the source is a lamp filament.

In Table I are given results of a test showing the effect of the position of the sector. A 15-mil (0.381 mm) tungsten lamp operated at a brightness temperature of about 2275°K was used as a background and readings were made on the current through a $2\frac{1}{2}$-mil tungsten pyrometer filament, for an apparent brightness match with a sector having two 1° openings. From the table it can be seen that the position of a sector of this size can cause an error of about 14°K for this condition if care is not taken as to its location. When a sector is used, it should be rotated so fast that no flicker is noticeable. Not only is an error apt to be made if the sector is not rotating fast enough, but the flicker is bothersome in making accurate brightness comparisons.

Absorbing Screens

A rotating sector is not an easily portable instrument and thus is not altogether satisfactory for commercial work, that is, work that requires that the pyrometer be frequently moved about. In such cases one must use some sort of absorbing screen.

Neutral Absorbing Screens

Unfortunately it is not easy to get an absorbing screen that is of neutral tint, that is, one that has the same transmission for all parts of the spectrum. Absorbing screens that are not neutral tint have a total transmission that depends upon the spectral distribution of energy from the source studied. The transmission for different conditions can be measured by comparison with sectored disks. This is sometimes very difficult since it is necessary to have a source with known distribution. For this a calibrated tungsten lamp can be used, obtaining the distribution from the color temperature.* A more convenient method

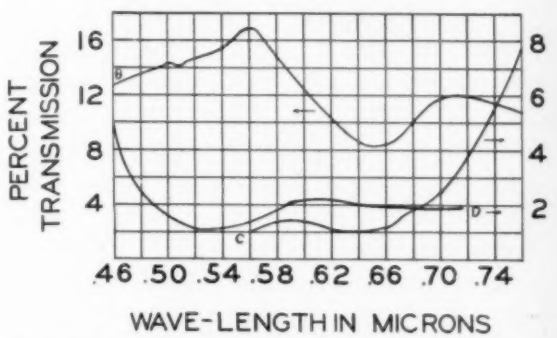


FIG. 8. Spectral transmission of various absorbing glasses. Curve *B*: Jena absorbing glass 1.5 mm thick. Curve *C*: Noviweld obtained from Corning Glass Works. Shade about 6. Curve *D*: Leeds & Northrup absorbing glass made of purple and green glass.

is to measure the spectral transmission of the screen and then calculate the total transmission for the different temperatures of the source (i.e.

* The color temperature of a source is the temperature necessary to operate a blackbody so that the color of its radiation will be the same as that of the source studied.

different distribution of energy) for which it is to be used. The total transmission T_A of an absorbing glass when used with a red glass (or any other color) is given by the following equation:

$$T_A = \frac{\int_0^\infty J(\lambda T) K_\lambda t_R t_A d\lambda}{\int_0^\infty J(\lambda T) K_\lambda t_R d\lambda}, \qquad (2)$$

where $J(\lambda T)$ (Wien's equation) is the energy distribution, K_λ the luminosity, t_R the spectral transmission of the red glass and t_A the spectral transmission of the absorbing glass. This integral can be calculated by the step-by-step method with sufficient accuracy for this purpose. This is done by forming the product as indicated by the equation for a number of equally spaced wave-lengths and then taking their sum.[11]

In Fig. 8 is shown the spectral transmission of three absorbing screens that are suitable for this kind of work if used with the red glass whose spectral transmission is shown by curve *C*, Fig. 5. In Fig. 9 is shown the total transmission of two of the absorbing screens with the red screen, as a function of the temperature of the source studied. In calculating an extrapolated temperature for a particular absorbing screen, the transmission of the screen to use is the one corresponding to the temperature that is measured. This may require a second approximation.

The total transmission of absorbing screens may depend upon the temperature of the screens themselves. In Table II are given the total transmissions for two different temperatures of the glasses for two of the screens the spectral transmissions of which are given in Fig. 8. When absorbing screens are used, they must be mounted so that they can always be put back in exactly the same position, since the transmission is apt to be different in different parts of the screen.

TABLE II. *Transmission of absorbing glasses at different temperatures.*

TEMPERATURE °C	NOVIWELD ABSORBING GLASS (%)	JENA ABSORBING GLASS (%)
20	1.70	8.96
102	1.55	8.90
200	1.39	8.87

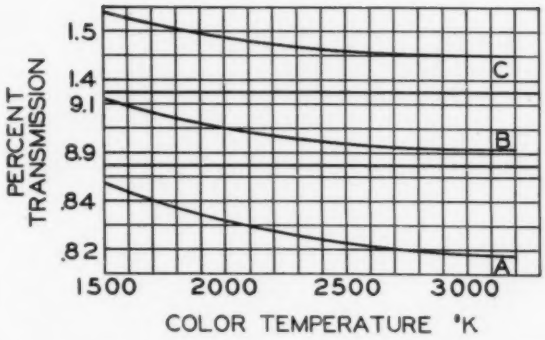


FIG. 9. Total transmission of absorbing glasses, as a function of temperature when used with red glass 4512, 5.8 mm thick. Curve *A*: two pieces Jena absorbing glass. Curve *B*: one piece Jena absorbing glass. Curve *C*: Noviweld glass from Corning Glass Works.

It has been stated[12] that the absorbing screen should have such a spectral transmission that it will give a color match between the source studied and the pyrometer filament for the range of the monochromatic screen. If this is done, a monochromatic screen of wider spectral transmission can be used. Specifically, absorbing screens[12] have been suggested such that

$$\frac{1}{T_1} - \frac{1}{T_2} = \text{const.} \qquad \text{(see Eq. (4))},$$

that is, that log T_a varies in such a manner as to compensate for the variation in λ_e. This makes for simpler calculations and makes it easier to combine screens to greatly extend the temperature scale. Such refinements are possible but are not necessary. What must be used is a monochromatic screen and an absorbing glass of such spectral transmissions that different observers will get practically the same reading. The sharper the cut-off on the short wave-length side and the farther towards the red end the cut-off is, the easier it is to find a neutral absorbing glass that will be satisfactory to use.

Calibration

The only radiation constant that enters into the calculations is c_2 and this comes in as a factor of the exponent in Wien's equation. It might be stated here that Wien's equation is generally used in calculations for optical pyrometers rather than the more exact form of Planck's equation because, for the range of the optical pyrometer up to about 4000°K (where the error is about 4°),

TABLE III. *Temperatures corresponding to different percentages of the radiation from a blackbody held at the temperature of melting palladium (1829°K) using a red glass with an effective wave-length which varies as is shown in column two. ($c_2 = 14{,}320\mu$ deg.).*

TRANSMISSION OF SECTOR	λ_e	T_2 IN DEGREES KELVIN
0.749	0.6654	1786
.499	.6655	1728
.2443	.6656	1632
.0830	.6658	1509
.0336	.6660	1426
.01668	.6662	1356
.00542	.6665	1267

Wien's equation is sufficiently accurate and is much easier to use.

It seems that a variation in the accepted value of c_2 will always be with us. The accepted value of the constant has been slowly decreased for a number of years and now Dr. Wensel[13] makes an analysis of all of the work done on this constant and points out that a larger value is indicated. Before Dr. Wensel's analysis the accepted value was $14{,}320\mu$ deg. Dr. Wensel concludes that this constant should be increased to $14{,}360\mu$ deg. If a temperature T_2 is obtained from calculations using one value of c_2, it can be reduced to the new value T_2' by the following formula

$$\left(\frac{1}{T_2}-\frac{1}{T_1}\right)=\frac{c_2'}{c_2}\left(\frac{1}{T_2'}-\frac{1}{T_1}\right). \tag{3}$$

To calibrate an optical pyrometer starting from fundamentals would be a great undertaking but fortunately this is not necessary. The fundamentals have been well worked out and standard methods are available. One method of calibrating is by direct comparison with a blackbody at a series of known temperatures. It is, in general, not easy to bring a blackbody to a number of definite temperatures, so methods have been devised to calibrate an optical pyrometer by comparison with a blackbody held at one standard temperature.[14] When a standard blackbody furnace is used for calibrating optical pyrometers, it is held either at the temperature of melting gold or melting palladium.

The standard radiator at the standard temperature gives one point on the calibration. To obtain another point, readings are taken of the current through the pyrometer filament for an apparent brightness match with a rotating sector, or absorbing glass of known transmission, between the pyrometer lamp and the standard blackbody. This will give a measure, in terms of the pyrometer current, of a brightness that is some known fraction of that of the standard radiator at the standard temperature. If monochromatic radiation is used, it is easy to calculate the temperature, T_2, of the blackbody corresponding to this brightness, that is, to this current through the pyrometer filament, from T_1 the standard temperature by the following formula derived from Wien's equation

$$\frac{1}{T_1}-\frac{1}{T_2}=\frac{\lambda\cdot\log T_A}{c_2\log e}, \tag{4}$$

where T_A is the transmission of the sector, or absorbing glass and λ is the wave-length used. If the measurements are made with a red glass in the eyepiece, the temperature that would correspond to this fraction of the brightness of the standard blackbody can be calculated just as before, excepting that in this case the effective wave-length of the red glass for the temperature interval is to be used. By using a number of sectors or absorbing glasses with different transmissions, points can be obtained for a curve showing the relation between the temperature and current. In column 3 of Table III are given a number of apparent temperatures each of which corresponds to the red brightness obtained when a rotating sector having the transmission given in column 1 is used between the pyrometer filament and a blackbody at the temperature of melting palladium.

The filament of the pyrometer lamp should not be heated to too high a temperature if it is to hold its calibration for any length of time. A safe temperature for a tungsten filament is somewhere in the neighborhood of 2000°K. Since it is often necessary to measure temperatures much higher than this, some means must be provided for this purpose.

EXTENDING TEMPERATURE SCALE

If a rotating sector or an absorbing glass of known transmission is used between the source being investigated and a calibrated pyrometer lamp, its apparent brightness will be reduced and

temperatures higher than the calibration of the pyrometer filament can be measured. In this case, the temperature is to be calculated from the temperature corresponding to the current through the pyrometer filament and the transmission of the sector or absorbing glass used by means of Eq. (4), except in this case for T_A, use the reciprocal of the transmission of the sector or absorbing screen, and then T_2 will come out greater than T_1.

A convenient method is to work out such extrapolated temperatures for the various sectors and absorbing glasses that are to be used, and plot the extrapolated temperatures against the temperatures as determined from the pyrometer reading. Such curves can then be used with any pyrometer using the same red glass, providing the same sectors or absorbing glasses are used.

In Table IV is given a series of such extrapolated temperatures using different sectored disks. In column 1 are given the initial temperatures; that is, the temperatures that would correspond to the pyrometer reading without any sector. In columns 3, 5, 7 and 9 are given the extrapolated temperatures corresponding to the same pyrometer readings when the sector, the transmission of which is given at the head of the column, is used between the pyrometer lamp and the source studied, and a red glass having the effective wave-length shown in columns 2, 4, 6 and 8 is used in the eyepiece.

In connection with some special work it was necessary to extend the calibration of an optical pyrometer to measure temperatures up to about 6000°K. This was done by using two absorbing glasses between the pyrometer lamp and the source being investigated. The spectral transmissions of the two glasses are shown by curves

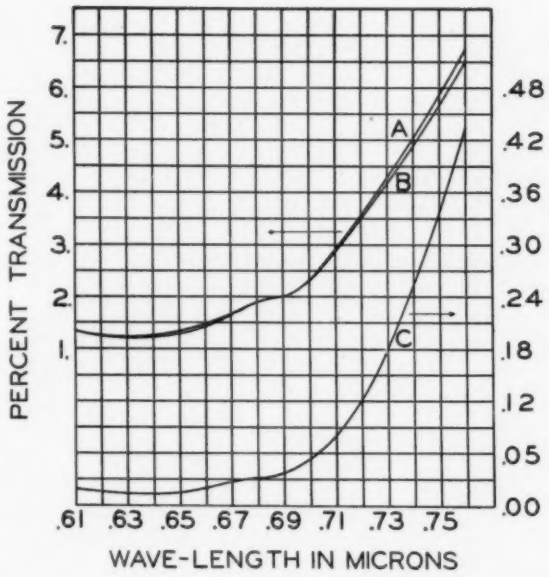


FIG. 10. Spectral transmission of two absorbing screens (Curves *A* and *B*) and the spectral transmission of the two together (Curve *C*).

A and *B*, Fig. 10, and that of the combination as shown by curve *C*. Since neither of these absorbing screens is of neutral tint, their combined total transmission is not the product of their individual transmissions. The combined transmission of any wave-length is, however, the product of their individual transmissions at this wave-length. Curve *C* was obtained from the product of the spectral transmissions of the two glasses at the different wave-lengths.

The transmission of either of these glasses alone was readily measured while a single absorbing glass with a transmission equal to that of the combination of the two would have been very difficult to measure. The total transmissions of these absorbing glasses for red radiation were

TABLE IV. *Extrapolated temperatures, using red glass, for various sectors with transmission as given.* $c_2 = 14{,}320\mu$ *deg.*

TRANSMISSION OF SECTOR	0.2443		0.0830		0.01664		0.00542	
INITIAL TEMPERATURE	λ_e	°K	λ_e	°K	λ_e	°K	λ_e	°K
1200°K	0.6675μ	1303	0.6673μ	1398	0.6670μ	1555	0.6668μ	1693
1300	.6671	1421	.6668	1530	.6665	1727	.6663	1899
1400	.6667	1541	.6664	1672	.6661	1909	.6659	2119
1500	.6663	1663	.6660	1816	.6657	2100	.6654	2354
1600	.6659	1788	.6656	1964	.6652	2299	.6650	2610
1700	.6655	1913	.6652	2117	.6648	2511	.6646	2887
1800	.6651	2042	.6648	2274	.6645	2738	.6643	3185
1900	.6647	2171	6645	2434	.6642	2967	.6640	3514

calculated from their spectral transmissions by Eq. (2) for various temperatures of incident radiation and are shown in Fig. 11. From the values of the total transmissions thus obtained, the extrapolated temperature for one glass and for the combination of the two were calculated by means of Eq. (4) and are shown in Table V. It

TABLE V. *Extrapolated temperatures using red glass for one absorbing glass and for two absorbing glasses having the transmissions shown in Figs. 8 and 9. $c_2 = 14{,}320\mu$ deg.*

INITIAL TEMPERATURE	TRANSMISSION OF ONE ABSORBING GLASS	EXTRAPOLATION TEMPERATURE FOR ONE ABSORBING GLASS	TRANSMISSION OF TWO ABSORBING GLASSES	EXTRAPOLATED TEMPERATURE FOR TWO ABSORBING GLASSES
1200°K			0.000238	2228
1300			.000233	2604
1400	0.0149	1922	.000230	3045
1500	.0148	2115	.000227	3565
1600	.0147	2321	.000224	4143
1700	.0147	2539	.000221	4965
1800	.0146	2770	.000218	5942

will be seen that when the two glasses are used together, temperatures may be measured up to about 6000°K.

Since it is not always convenient or possible to operate a blackbody for the calibration of an optical pyrometer, some substitute is necessary. A tungsten lamp with either a wire or ribbon filament, can be calibrated as a standard of brightness and used for this purpose. It is sometimes convenient to have the filament calibrated so that the currents are known for the brightnesses as observed through a definite monochromatic glass for the blackbody at the temperature of melting gold and melting palladium.

It has been found that such a lamp, if not operated at a higher temperature than that necessary to give a red brightness the same as that of a blackbody at the palladium point, will have a very long life.

About twenty-six years ago two 7.5-mil hairpin filament vacuum tungsten lamps were calibrated in the laboratory at Nela Park as standards of the same brightness observed through our red glass, as a blackbody at the melting point of palladium. For about ten years these lamps were checked from time to time against the standard blackbody at this temperature. For the past fifteen years we have not operated our blackbody and these two lamps were our only standard of brightness corresponding to the palladium point. About two years ago Dr. Wensel of the National Bureau of Standards calibrated these lamps at the currents for a brightness corresponding to the palladium point. Dr. Wensel's calculations showed these two lamps now agreed with the National Bureau of Standards value of the brightness of a blackbody at the palladium point, for the effective wave-length used to about 1°C.

Such standard lamps are very valuable for a hurried check on the calibration of an optical pyrometer since they can be calibrated at several points over the range desired to calibrate the pyrometer lamp. These standard lamps can be calibrated at a much higher temperature than 1828°K and still have a satisfactory life. It must be remembered, however, that these are supposed to be standard lamps and that this is the brightness temperature and that the true temperature is about 150°C higher than the brightness temperature (at 1800). Another point to keep in mind is that a tungsten lamp, pyrometer-calibration standard, must be standardized for the same effective wave-length as that of the monochromatic screen on the pyrometer where it is to be used.

Accuracy

ACCURACY TESTS

A number of experiments have been made that show the accuracy that might be expected

TABLE VI. *Results obtained with a disappearing-filament type of pyrometer by inexperienced observers.*

OBSERVER	VALUE OBTAINED FOR TEMPERATURE, AS AN AVERAGE OF SIX READINGS, (°K)		VARIATION OF SINGLE READINGS FROM MEAN (°K)
Standards	1438	1643	
(1) L.C.	1439	1643	4
(2) H.W.	1438	1642	3
(3) F.G.	1439	1642	2
(4) E.H.	1436	1644	3
(5) E.W.	1436	1636	5
(6) L.R.	1436	1640	2

in the use of the disappearing-filament type of optical pyrometer. In the first experiment, readings were made by a number of observers

who had no experience in this kind of work. The instrument used was the laboratory form of pyrometer. The resistance that controls the current through the pyrometer filament was so chosen that the sliding contact had to be moved quite a distance in order to change the apparent brightness of the filament by an appreciable amount. The current was measured by means of a potentiometer.

In Table VI are given the results of this experiment. Observers 1 and 2 were high-school graduates with several months' experience as laboratory assistants. Observer 3 was a man with several years' experience in shop work. Observer 4 was a man with several years' experience in a lamp factory. Observers 5 and 6 were girls from the lamp factory; No. 5 had no experience with this kind of work, while No. 6 had had experience with the photometer.

The table shows that but a single observer made an error greater than 3°K in the temperature as obtained from the average of six readings. In no instance was a value of temperature obtained from a single reading that differed more than 5° from the mean of the set of readings.

In the second experiment four experienced observers made readings with two pieces of Jena red glass No. 4512 (spectral transmission shown by curve *C*, Fig. 5) in the eyepiece of the pyrometer, on the apparent brightness of a particular

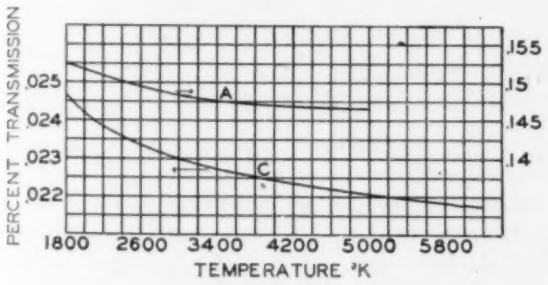


FIG. 11. Total transmission for red radiation of the absorbing screen whose spectral transmission is shown by Curve *A*, Fig. 10, and of the two absorbing glasses whose spectral transmission is shown by Curve *C*, Fig. 10.

source as observed first through a rotating sector with two 1° openings, second through the Noviweld absorbing glass having the spectral transmission shown by curve *C*, Fig. 8, and third through two pieces of Jena absorbing glass having the spectral transmission shown by curve, *B*, Fig. 8. The source used was a 15-mil tungsten lamp operated at a color temperature of 2610°K. Values of the current through the pyrometer filament thus obtained are given in Table VII. The maximum range with the two glasses occurs for K.H.M. and W.E.F. for the Noviweld glass when the Jena red glass No. 4512 was used. This amounted to about 1 percent in brightness and to less than 3° in temperature at about 2500°K.

TABLE VII. *Results obtained by experienced observers using different red glasses and different absorbing glasses.*

		CURRENT THROUGH PYROMETER FILAMENT FOR APPARENT BRIGHTNESS MATCH WITH			
OBSERVER	RED GLASS USED	DIRECT	2° SECTOR	NOVIWELD ABSORBING GLASS	TWO JENA ABSORBING GLASSES
I.A.V.	Jena No. 4512	0.4343	0.3358	0.3804	0.3547
K.H.M.	Jena No. 4512	0.4343	0.3361	0.3807	0.3546
W.E.F.	Jena No. 4512	0.4343	0.3361	0.3803	0.3546
A.G.W.	Jena No. 4512	0.4343	0.3358	0.3805	0.3547
I.A.V.	Corning Red		0.3380	0.3784	
K.H.M.	Corning Red		0.3380	0.3785	
W.E.F.	Corning Red		0.3380	0.3783	
A.G.W.	Corning Red		0.3378	0.3784	

A third experiment[15] shows, in another way, what results are to be expected with the optical pyrometer. A number of tungsten filament lamps were calibrated at the laboratory at Nela Park for a wide range of brightness temperatures (1200–2700°K) and sent to the National Bureau of Standards, the National Physical Laboratory of England, the Physikalisch-Technischen Reichsanstalt in Berlin, the Laboratoire Central in Paris, the General Electric Research Laboratory at Schenectady, the Physics Laboratory at the University of Wisconsin, the Laboratory of the Philips Glowlampworks in Eindhoven, and the laboratory of the Osram Lamp Company at Berlin. In some cases two lots of lamps were exchanged and the final outcome was a check that was much better than one would expect in this kind of work when one considers that in each laboratory the pyrometer was calibrated against a blackbody, the lamps operated and their temperature measured with a pyrometer.

Another test that shows the accuracy that can be obtained with this type of pyrometer is the

comparative measurements made on a carbon arc conducted by Dr. Chaney.[16] These arcs were measured in the laboratory of the National Carbon Company, in our laboratory here at Nela Park, and in the laboratory of the National Bureau of Standards, with the results given in Table VIII, which indicate an agreement better

TABLE VIII. *Brightness temperature of a special carbon arc as measured in three laboratories.*

National Carbon Co.	3814°K
Nela Park	3812*
National Bureau of Standards	3821

* Corrected to international temperature scale since data published by Dr. Chaney.

than one has a right to expect. The determination of the melting point of platinum that occurred in the establishment of the Waidner and Burgess[17] standard of light intensity can be given as another check on the accuracy obtainable. In establishing this scale, platinum was melted in a special blackbody in several standardization laboratories with the results given in Table IX. These results

TABLE IX. *Melting point of platinum as determined in connection with establishment of Waidner and Burgess standard of light intensity.*

National Bureau of Standards	1773.5°C
National Physical Laboratory	1773.3
Physikalisch-Technischen Reichsanstalt	1773.8

are the average of a number of settings but nevertheless they indicate the high degree of accuracy that can be obtained with very special care.

Table X was prepared to show what errors in the final temperatures would result from errors in certain constants or from certain other causes. The results given in this table indicate the care necessary in calibrating and operating this type of optical pyrometer to reach the standard of accuracy desired.

Temperatures of Nonblackbodies

The discussion concerning the optical pyrometer thus far applies to observations, comparisons, and computations for a blackbody. The optical pyrometer is, however, a very useful instrument for studying the radiating characteristics of nonblackbodies as well, and it has been used in many such investigations.

If proper precautions are taken, quite accurate results can be obtained with this instrument in studying nonblackbodies i.e., those which radiate less for some or all wave-length intervals than a blackbody. Most nonblackbodies can be so prepared, i.e., surface conditions, that their radiation characteristics are quite constant for any definite temperature.

An optical pyrometer measures the brightness of a surface for a definite wave-length interval and a temperature can be calculated from this brightness under the assumption that the brightness is obtained from a blackbody. Thus, if a nonblackbody has the same brightness as a blackbody at a temperature of 1500°K, it will be

TABLE X. *Changes in temperature of 2400° and 3000°K extrapolated from 1800°K as initial temperature, using Wien's equation, due to various changes.*

Variation leading to error	Percentage change			Actual change (°K)		
	1800	2400	3000	1800	2400	3000
Change of 1% in initial temperature	1.0	1.30	1.70	18.0	32.0	50.0
Change of 3°K in initial temperature				3.0	0.5	8.0
Using a wave-length, 1% in error		0.30	0.70		8.0	20.0
0.001μ error in wave-length		0.50	0.10		1.2	3.0
If in extrapolating the λ_e of red glass between 1300° and 1800°K is used (see Fig. 6)		0.10	0.30		2.4	7.5
Calibrating pyrometer filament against tungsten lamp as background that was standardized with a red glass different from one used in pyrometer being calibrated. Suppose λ_e to change from 0.665μ to 0.650μ				3.5		
Error of 1% in value used for transmission of sector or absorbing glass		0.11	0.14		2.7	4.2
Variation of 1% in current through 2½-mil pyrometer filament	0.5	0.70	0.80	9.0	16.0	25.0

said to have a brightness temperature of 1500°K which is lower than its true temperature.

To obtain the true temperature from these brightness temperatures, one must know something about the radiating characteristics of the source studied. In this particular instance one wants to know the ratio of the brightness of the source studied to that of a blackbody for the same temperature and wave-length interval. This ratio is called the emissivity and its significance and methods of measuring it will be discussed in the following paper. The true temperature, T, can be calculated from the brightness temperature, S_λ, and the emissivity, e_λ, by the following equation.

$$\frac{1}{T}-\frac{1}{S_\lambda}=\frac{\lambda_e \log e}{c_2 \log e_\lambda}. \qquad (5)$$

If a spectropyrometer be used for these measurements, the wave-length will be quite definitely determined and there will be no question concerning the wave-length used. Can this be done if a monochromatic screen is used?

The first question, of course, is the wave-length to which this brightness temperature should be ascribed. The brightness temperature, S_λ, must be ascribed to a wave-length such that the energy emitted by a blackbody per unit area at temperature $T(=S_\lambda)$, for this wave-length will equal that emitted per unit area by the source for the same wave-length. Thus, there are two sources with different spectral distributions that have the same brightness when observed through the red screen, a blackbody at temperature $T(=S_\lambda)$ and the source studied, which is at a brightness temperature S_λ. Call the color temperature of the source T_c. As these two distributions are different and yet the sources have the same brightness, the curves representing these distributions must cross if they are plotted with energy emitted per unit area against wave-length. The point at which these two curves cross evidently gives the wave-length to which the brightness temperature, S, is to be ascribed.

It can be shown[6] that the wave-length for which these two curves cross is the effective wave-length for the temperature interval between a temperature $T(=S_\lambda)$ of a blackbody and T_c, the color temperature of the source studied. This means that the different brightness temperatures of a nonblackbody will, in general, be ascribed to different wave-lengths.

Sometimes it is desirable to know the brightness temperature over quite a range of temperatures for the same wave-length. If the color temperature of the source is known, the brightness temperature can be calculated for any wave-length when it is known for one wave-length. Thus, for a source at a color temperature, T_c, using Wien's equation and the conditions that hold for color match, the following relation between two brightness temperatures ($S_{\lambda 1}$ and $S_{\lambda 2}$) for two wave-lengths (λ_1 and λ_2) can be derived.

$$\frac{1}{S_{\lambda 2}}=\frac{\lambda_2}{\lambda_1}\left(\frac{1}{S_{\lambda 1}}-\frac{1}{T_c}\right)+\frac{1}{T_c}. \qquad (6)$$

For a good red glass, this correction is small. If a double thickness (6.8 mm) of the red glass known as Jena Rotfilter No. 4512 (spectral transmission shown by curve C, Fig. 5), is used before the eyepiece of the pyrometer, this correction when applied to the brightness temperature of such a metal as tungsten will be small. The effective wave-length of this red glass is 0.6657μ, for the range between brightness and color temperature of tungsten, at a brightness temperature of 1600°K; and for this same range for tungsten at a brightness temperature of 3000°K, is 0.6626μ. If the higher brightness temperature is corrected to a wave-length 0.6657μ, the correction will amount to about -2°K. For most work when using this screen, this correction will be negligible.

Thus, just as definite results can be obtained using an optical pyrometer with a good monochromatic screen as with a spectropyrometer. If one wants to study the radiating characteristics of a particular source for different parts of the spectrum, it is only necessary to obtain a monochromatic screen for that part of the spectrum.

If the effective wave-length of the red glass used is known for different temperature ranges, the results can be treated just as definitely as if an absolutely monochromatic screen were used; in addition, the red glass has the added advantage of transmitting enough light to enable very accurate brightness comparisons to be made.

Bibliography

1. Schuster and Nicholson, *Theory of Optics*, p. 152.
2. Worthing, Astrophys. J. **36**, 345 (1912).
3. Worthing and Forsythe, Phys. Rev. **4**, 163 (1914); Fairchild and Hoover, J. Opt. Soc. Am. **7**, 543 (1923).
4. Mendenhall, Phys. Rev. **33**, 74 (1911); Henning, Zeits. f. Instrumentenk. **30**, 61 (1910); Astrophys. J. **49**, 237 (1919).
5. Astrophys. J. **42**, 296 (1915).
6. Gen. Elec. Rev. 749 (1917).
7. J. Opt. Soc. Am. **4**, 305 (1920).
8. 1920 Pyrometer Symposium, 298.
9. Astrophys. J. **42**, 302 (1915).
10. Reference 9, p. 303.
11. Adams, Rev. Sci. Inst. **4**, 623 (1933).
12. Foote, Mohler and Fairchild, J. Wash. Acad. Sci. **7**, 545 (1917).
13. Nat. Bur. Stand. J. Research **22**, 375 (1939).
14. Mendenhall, Phys. Rev. **33**, 74 (1911); See also Chem. and Met. Eng. **22**, 373 (1920).
15. Phys. Rev. **38**, 1247 (1931).
16. Trans. Electro. Chem. Soc. **67**, 167 (1935).
17. Reoser, Caldwell and Wensel, Nat. Bur. Stand. J. Research **6**, 1119 (1931); Schofield, Proc. Roy. Soc. **146**, 792 (1934); Hoffman and Tingwaldt, Physik. Zeits. **35**, 434 (1934).

Symposium on Tensile Test of Metals

By John M. Lessells

The American Society for Testing Materials will hold a Symposium at their Annual Meeting, Atlantic City, June-1940, which will be devoted to the presentation and discussion of a group of papers dealing with the Tensile Test of Metals with a view to a better understanding in the application of these test results to design questions. The value of such a presentation will be very largely in the amount and character of the discussion which takes place. In order to prepare the way for such discussion the writer, who is Chairman of the Committee consisting of the following members, Colonel G. F. Jenks, Mr. N. L. Mochel, Professor H. F. Moore and Mr. R. E. Peterson organizing this Symposium, has set down some observations on the Tensile Test and some of the various points which are expected will be covered by the Symposium material. Some of these are a restatement of known facts, while others are still not well understood.

It is to be hoped that all those engineers who are interested in broadening the basis of our present knowledge will take part in the discussions so that points at present hazy will become clarified.

Information of the Tensile Test in Design

The choice of working stresses is of the utmost importance to the engineer and if the design is to be sound it is essential that very clear ideas regarding them must be obtained. It is largely on account of this fact that recent efforts have been made by the Applied Mechanics Division of the American Society of Mechanical Engineers[1] and also by the Vereines Deutscher Ingenieure[2] to establish codes for choice of working stresses.

In this work, which only refers to the condition of elastic stability, the generalized condition of stress is represented by a variable stress superimposed on a steady stress. In the extreme cases the stress will either be steady or variable; the material properties corresponding to these conditions being the endurance limit under completely reversed stress on the one hand and the tensile strength on the other. It is therefore apparent that in any consideration of codes for working stresses the tensile strength must play an important part.

In the wide variety of materials used by the engineer there are very decided differences in the tensile test characteristics. For instance with annealed copper, such as used for commutator bars, we have a material with little or no elasticity and very great ductility, while in the case of spring steels we have little or no ductility with very high elastic limits. Then again we have steels with a very well-defined yielding and others where this sharp definition at yield is not so evident. Since, as above, the tensile test characteristics must influence design conditions it seems fitting that consideration must be given to these widely divergent properties.

Aims and Scope of Symposium

In order to bring before the materials engineer the viewpoint of the designing engineer and to allow clarification of certain of the characteristics of the tensile test, some of which have been mentioned here, the present Symposium is being organized.

The Symposium will consist of three papers dealing with the more fundamental aspects, the strength features, and the ductility features. The specific titles and authors are as stated below:

1. The Tensile Test, Professor C. W. MacGregor
2. The Strength Features of the Tensile Test, Professor F. B. Seely
3. The Ductility Features of the Tensile Test, Dr. H. W. Gillett

Arrangements have been made to have the papers preprinted and distributed considerably in advance of the date of presentation and it is to be hoped that a very complete discussion of each will result. If the Symposium and discussion result in a better understanding of the behavior of materials leading to their better application the Committee will feel amply repaid for their efforts.

[1] C. R. Soderberg, "Working stresses," Design Data, A.S.M.E. Publication, 1939, on "Strength of materials" (reprinted from various issues of *The Journal of Applied Mechanics*).
[2] Schaubilder, "Dauerfestigkeit," Zeits. V.D.I., Supplement No. 1, Vol. 77, 1933; No. 2, Vol. 77, 1933; No. 3, Vol. 78, 1934; No. 4, Vol. 78, 1934; No. 5, Vol. 78, 1934.

Temperature Radiation Emissivities and Emittances*

BY A. G. WORTHING

University of Pittsburgh, Pittsburgh, Pennsylvania

Introductory

THE word emissivity comes from the Latin "emittere" meaning to send out. In accord with that primary meaning, an emissivity for a given material is a measure of the ability of a body made of that material to send out radiant energy. Such an ability might be expressed in terms of the rate of emission per unit of surface area. Some use the word emissivity in this sense and speak of an emissivity of 50 watts/cm², for instance; but general usage now expresses this ability differently. A comparison is made instead with a like ability of a complete or perfect emitter, a blackbody, at the same temperature.

In the interior of an opaque body of uniform temperature throughout, at distances from its surfaces yielding practically complete absorption for entering radiation, blackbody conditions are found. If the body is a blackbody, the rate of emission of radiant energy from its surface will correspond to the unhindered passage of radiant energy from such an interior. If the body is a nonblackbody, the rate of emission will be lessened because of the hindrance, in the way of reflection, occurring at the surface. With these facts in mind, it is natural to express a sending out ability, that is an emissivity, for nonblack material as a ratio, that for an opaque body composed of the nonblack material to the corresponding ability for a blackbody at the same temperature.

In accord with the usage that an *ivity* ending shall denote a characteristic of a material, the term emissivity is limited to a comparison with a blackbody under conditions where the individual characteristics of bodies composed of the material under consideration, are eliminated. Since the radiating characteristics of a body depend in part upon its opaqueness and the roughness of its surface, these features must be considered in the forming of an acceptable emissivity definition. Ease of specification and of reproduction are the obvious reasons for requiring that the emissivities of materials shall refer to comparisons made with opaque specimens whose surfaces are polished. Accordingly the emissivity of a material is defined as the ratio of a rate of emission of radiant energy by an opaque body with polished surface composed of that material as a consequence of its temperature only, to the corresponding rate for a blackbody at the same temperature. Thus a rate of emission of radiant energy per unit area by tungsten at 2000°K is 23.7 watts/cm², the corresponding rate for a blackbody is 91.8 watts/cm², and the total hemispherical emissivity of tungsten at 2000°K is 0.258. There are several types of emissivity.

Two other terms, namely emissive power and emission factor, have been and are still used to some extent to indicate what we now mean by emissivity. It is also true that, to some extent, as stated above, the term emissivity has been and is used to designate the quantity now called radiancy.

In accord with the usage that an *ance* ending shall denote a characteristic of a body or of a portion of a body rather than of the material composing it, an emittance for a body at some constant temperature is defined as the ratio of a rate of emission of radiant energy by the body in consequence of its temperature only to the corresponding rate for a blackbody at the same temperature. The condition of the surface of the body, polished or not, oxidized or not, and the condition as to opaqueness are immaterial. For a tungsten filament at 2000°K whose surface has been roughened greatly a hemispherical total emittance of 0.5 in contrast with the corresponding emissivity of 0.258 is not impossible. If

* Presented at the American Institute of Physics Symposium on Temperature, Its Measurement and Control in Science and Industry, New York, November 2, 1939.

the body is opaque the emittance has the emissivity as its lowest limiting value. For a glass rod at 1000°K, however, due to its nonopaqueness, one expects emittances less than the emissivities. In place of a normal spectral emissivity for visible light of about 0.96, one may obtain a corresponding emittance of say 0.10. Often the emittances of composite bodies, as of a shellacked piece of steel, are of interest. Their probable values range from zero to unity.

Types and Definitions

There are various standpoints from which a nonblackbody's radiating ability may be considered. The two most common are the total heating effects per unit area taking account of all wave-lengths of radiation, and the spectral heating effects taking account of only a very limited range of wave-lengths. Corresponding thereto we have total and spectral emissivities. If the standpoint is one of visual effects rather than of heating effects produced by the radiation, we obtain a luminous, or visible, emissivity. Corresponding to a comparison with a blackbody, not at the same temperature but at the same visual color instead, we speak also of a color emissivity. Other emissivities such as an erythemal emissivity might be defined but the writer is not aware of their actual use.

For each of the foregoing types of emissivity, at least two subdivisions are to be recognized, a normal and a hemispherical emissivity. The cause for this is the departure from Lambert's cosine law exhibited by the radiation from nonblackbodies. Illustrations of such variations are shown in Fig. 1 spectrally for tungsten[44] and in Fig. 2 totally for platinum.[2] One might, if one wished, speak also of an emissivity at any prescribed angle with respect to the normal. Such emissivities are not commonly listed, however.

In giving precise definitions for the various emissivities, we need, in describing radiation sources, to make use of three well-recognized terms and a fourth which is not well recognized. They are[8] radiancy, steradiancy, brightness, and "luminous radiancy." The radiancy of a source of radiation is its rate of emission of radiant energy per unit of area. It is commonly expressed in watts/cm². The steradiancy of an element of a source of radiation in a given direction is its rate of emission of radiant energy in that direction per unit area and unit solid angle. It is commonly measured in watts/(cm² steradian). The brightness of an element of a source of radiation in a given direction is its rate of emission of light in that direction per unit area and unit solid angle. It is analogous to steradiancy and is commonly expressed in lumens/(cm² steradian) or in candles/cm². The "luminous radiancy" (the not well-recognized term) of a source of light is its rate of emission of light per unit of area. It is analogous to radiancy and is expressed in lumens/cm².

We are now ready to give precise definitions for the various emissivities, each of which is defined for an element of polished surface of an opaque body at constant temperature.

A hemispherical total emissivity, ϵ_{ht}, for the polished surface of an opaque portion of material

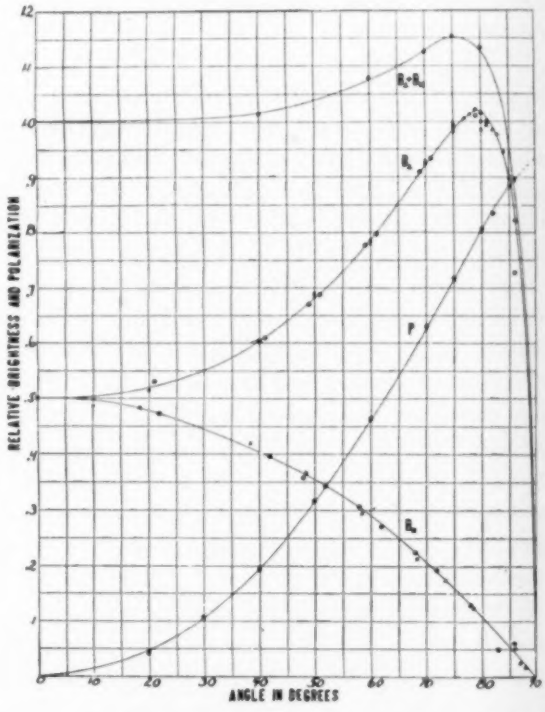


FIG. 1. Showing for tungsten, at temperatures ranging from 1750°K to 2470°K, relative spectral brightnesses ($\lambda=0.665\mu$) for the principal polarized light components $B_\perp$ and $B_{||}$ and the natural light $B_\perp+B_{||}$ and the polarization of the natural light P. The variation from Lambert's cosine law is shown by the $B_\perp+B_{||}$ curve, as well as the variation of the emissivity $\epsilon_{\theta\lambda}$ with angle of emission. The $B_\perp$ and $B_{||}$ curves show similar emissivity variations for the two corresponding polarized components.

at constant temperature is the ratio of its radiancy to that of blackbody material at the same temperature.

A normal total emissivity, ϵ_{nt}, for the polished surface of an opaque portion of material at constant temperature is the ratio of its normal steradiancy to that of blackbody material at the same temperature.

A hemispherical spectral emissivity, $\epsilon_{h\lambda}$, for the polished surface of an opaque portion of material at constant temperature is the ratio of its spectral radiancy to that of blackbody material at the same temperature.

A normal spectral emissivity, $\epsilon_{n\lambda}$, for the polished surface of an opaque portion of material at constant temperature is the ratio of its normal spectral steradiancy to that of blackbody material at the same temperature.

A hemispherical luminous emissivity, ϵ_{hl}, for the polished surface of an opaque portion of material at constant temperature is the ratio of its "luminous radiancy" to that of blackbody material at the same temperature.

A normal luminous emissivity, ϵ_{nl}, for the polished surface of an opaque portion of material at constant temperature is the ratio of its normal brightness to that of a blackbody material at the same temperature.

A hemispherical color emissivity, ϵ_{hc}, for the polished surface of an opaque portion of material at constant temperature is the ratio of its "luminous radiancy" to that of blackbody material having the same color as viewed visually.

A normal color emissivity, ϵ_{nc}, for the polished surface of an opaque portion of material at constant temperature is the ratio of its normal brightness to that of blackbody material having the same color as viewed visually.

In use there has been considerable confusion due to a failure to distinguish between hemispherical and normal emissivities. This has been particularly true of total emissivities.

Emissivities, both spectral (Fig. 1) and total (Fig. 2), vary with the emission angle. The definitions for the various types belonging to this group are obvious. They may be designated by $\epsilon_{\theta\lambda}$, $\epsilon_{\theta t}$, $\epsilon_{\theta c}$, and $\epsilon_{\theta c}$. Types of emittances are equal in number to the types of emissivities, and we properly speak of the hemispherical total emittance of a body and of its normal spectral emittance. Emittances will be distinguished by primes, thus ϵ_{nt}', ϵ_{ht}', $\epsilon_{h\lambda}'$, etc.

Closely connected with the terms emissivity and emittance, in theory and practice are the terms reflectivity and reflectance, and absorptivity and absorptance. A *reflectivity* is defined for an opaque, polished portion of material as the ratio of a rate of reflection of radiant energy from its surface to the corresponding rate of incidence of radiant energy upon it. An *absorptivity* is defined for an opaque polished portion of material as the ratio of a rate of absorption of radiant energy by it to the corresponding rate of incidence of radiant energy upon it. Since all of the radiant energy which is incident on an opaque element of surface is necessarily either absorbed or reflected, the sum of a reflectivity and its corresponding absorptivity is necessarily unity. As with emissivity, we speak of spectral and total, normal and hemispherical reflectivities and absorptivities.

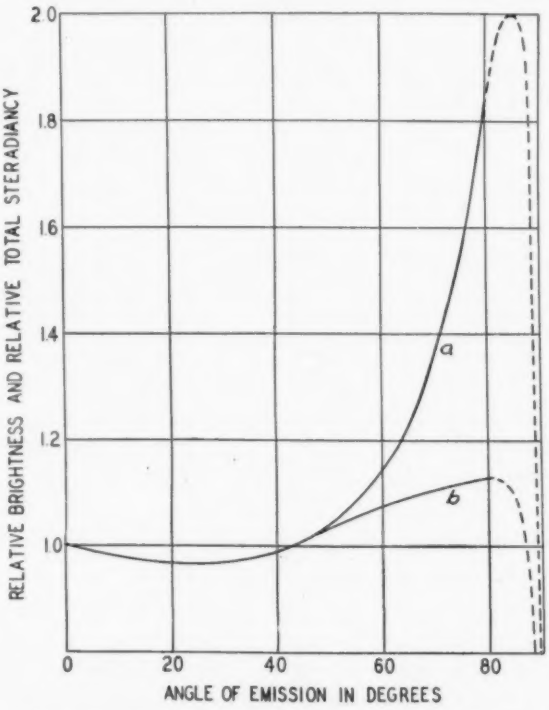


FIG. 2. Showing for platinum, at incandescence, the variation (*a*) of total steradiancy, and (*b*) of spectral brightness in the red with angle of emission.

For an opaque-walled cavity which has a uniform temperature throughout and is therefore in equilibrium, it is easy to show that a body in the

interior is emitting radiation from its surface at just the rate that it is absorbing radiation from the walls which is incident on its surface. Not only is this true for total hemispherical rates of emission and absorption, but it is also true for the normal and the spectral rates for the con-

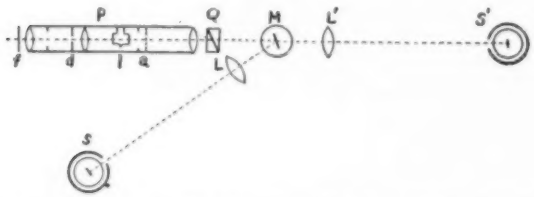


FIG. 3. Arrangement of apparatus for obtaining spectral emissivities by a reflectivity method in the visible region. S is a nearly enclosed light source, M a lamp containing a ribbon filament whose reflectivity is to be measured, Q a Rochon double image prism, L a lens imaging S on the ribbon filament, P a disappearing filament pyrometer with pyrometer lamp at l, absorbing screen at a, limiting diaphragm at d, and colored pyrometer glass filter at f. S, L, and M are supported on a rotatable mount with a vertical axis at the center of M. S' and L' are positions corresponding to S and L for the determination of the unreflected brightness of the image of S.

ditions described, generally known as blackbody conditions. We may therefore write

$$(\epsilon = a = 1 - r)_T, \tag{1}$$

the subscript T at the right indicating that not only the ϵ, the a, and the r are for the temperature T, but that the incident radiations also are such as occur in a blackbody cavity at the temperature T. The equation then holds separately for each type of ϵ, a and r.

If, however, the incident radiation has a spectral distribution different from that characteristic of a blackbody at the temperature of the element of surface in question, the simple relations given in the equation no longer hold for the total emissivities. The corresponding spectral values for ϵ, a and r are, however, as one will perceive, independent of spectral distributions and are therefore completely interrelated at all times by Eq. (1) as shown. To illustrate, for tungsten at 2000°K, $\epsilon_{n\lambda}$ at 0.665μ is 0.435 and the corresponding absorptivity and reflectivity values are 0.435 and 0.565. The value of ϵ_{ht} for the same temperature is 0.260, but what the values of a_{ht} and r_{ht} are cannot be stated unless the spectral distribution of the incident radiation is known. If it is that of blackbody radiation corresponding to 2000°K, a_{ht} and r_{ht} are 0.260 and 0.740.

Measurement of Spectral Emissivities

Optical Constants Method

In texts on physical optics, there are shown (1) the dependency of the reflectivity and the emissivity of a material on its optical constants, that is upon its index of refraction and its absorption coefficient, and (2) how these constants may be determined experimentally. For further details regarding the optical constants method, such texts should be consulted.

Reflectivity Method for Obtaining $\epsilon_{n\lambda}$

This method for obtaining a spectral emissivity depends upon the relation

$$\epsilon_{n\lambda} = 1 - r_{n\lambda}, \tag{2}$$

or upon the corresponding relation in case $\epsilon_{h\lambda}$ is desired. In either case, the experimental procedure involves three determinations of spectral brightness or of spectral steradiancy.

To illustrate, suppose that one wishes to determine $\epsilon_{n\lambda}$ for tungsten, say at 1500°K, in the visible region. As the tungsten specimen, let him select a uniform, polished ribbon mounted in a glass lamp bulb which is either evacuated or contains an atmosphere which does not react chemically with the tungsten, and, as an arrangement of apparatus, that of Fig. 3, except that the double-image Rochon prism Q may be eliminated if one is not interested in polarized components. Let $B_{\lambda 1}$ be the spectral brightness of the mirror resulting from its own high temperature, $B_{\lambda 2}$ that of the source S in position S' as seen, with M slightly displaced, through the bulb containing the polished tungsten ribbon, and $B_{\lambda 3}$ that of the source in position S as seen reduced by reflection from the mirror ribbon, superposed on the spectral brightness which results from the mirror's own high temperature. The reflectivity $r_{n\lambda}$, as a first approximation, is then given by

$$r_{n\lambda} = (B_{\lambda 3} - B_{\lambda 1})/B_{\lambda 2}. \tag{3}$$

Strictly speaking, one obtains thus an $r_{\theta\lambda}$ where θ is half of the angle between the line SM of Fig. 3 and the axis of the pyrometer. The correction to be applied to yield $r_{n\lambda}$ when not negligible may be obtained by extrapolation. Eq. (2) serves for obtaining $\epsilon_{n\lambda}$. Inspection shows that no corrections need be made for absorption of light by the

glass of the bulb enclosing the mirror M. For accuracy it is desirable that $B_{\lambda 1}$ shall be considerably less than $B_{\lambda 3}$.

The method described has been much used by the writer[44] not only for determining $\epsilon_{n\lambda}$, but also $\epsilon_{\theta\lambda}$ for various angles of emission and for the two normal polarized components of emitted light as well as the light taken as a whole.

Langmuir,[19] applied this method to tungsten at its melting point. In a molten terminal of a metal arc, there may be seen mirrored images of several orders, the first being that of the opposing terminal, the second that of the first terminal mirrored in the second, etc. Spectral brightnesses just inside and just outside such a first-order image for terminals just alike and at the same temperature, yield as above the $r_{\lambda n}$ and then $e_{\lambda n}$.

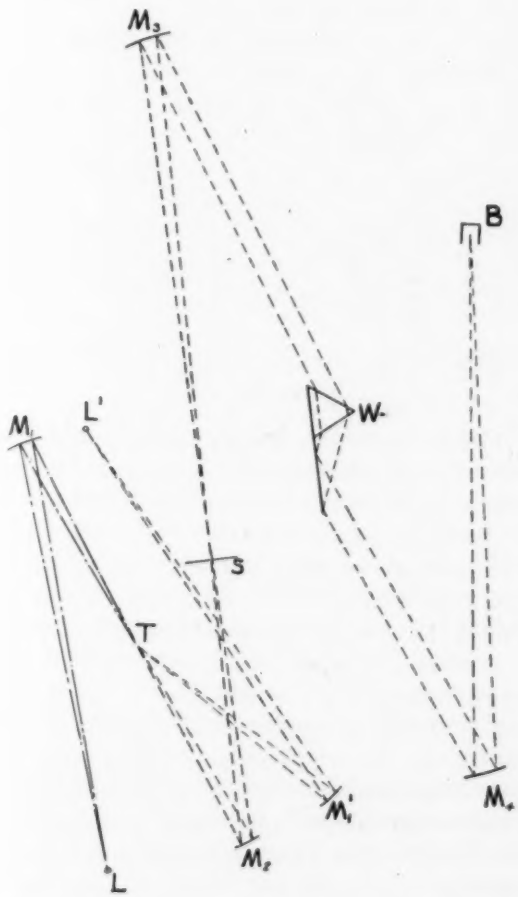


FIG. 3a. Diagram showing apparatus used by Weniger and Pfund, reference 42, in the determination of normal spectral emissivities $\epsilon_{n\lambda}$ in the infra-red.

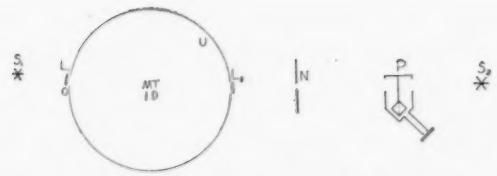


FIG. 4. Apparatus for the determination of a hemispherical emissivity in the visible region. U, Ulbricht sphere, T, polished hemispherical target, M, plane mirror, S_1S_2 light sources, L_1L_2 lenses, N, opaque screen with opening to just include the image of T formed by L_2. P, photometer head, F, filter for yielding approximately monochromatic light of the desired wave-length.

Shackelford,[33] using a somewhat open helical coil of polished tungsten ribbon which was heated electrically to a uniform temperature, measured likewise the spectral brightness of the ribbon within the coil just inside and just outside an image. Values for $\epsilon_{n\lambda}$, as in the case of Langmuir's measurements, followed simply.

Obviously the procedure outlined may be used in the infra-red region as was done by Weniger and Pfund[42] (Fig. 3a). Of course a receiver responding to the thermal effects of radiation was substituted for the pyrometer.

Reflectivity Method for Obtaining $\epsilon_{\lambda\lambda}$

To obtain a hemispherical spectral emissivity by a reflection method is equally simple in theory, though not so in practice. A most direct method for the visual region employs the Ulbricht sphere of spherical photometry with its inner coating of highly reflecting and highly diffusing paint. A small polished hemisphere T, (Fig. 4) of the material being studied with the convex surface symmetrically oriented with respect to the photometric axis replaces the ordinary target. The source S supplying the light within the sphere should be so located that initially as much as possible of its utilized luminous flux shall be incident on a small portion only of the inner surface of the sphere back of the target T on the axis of the system at O. Insofar as the paint is perfectly diffusing, the remainder of the inner surface, except for the two small openings, will then be uniformly bright and will illumine the hemisphere uniformly. Under these conditions, the ratio of an average spectral brightness of the small hemisphere as viewed by the reflected light, less its own natural spectral brightness, to the corresponding spectral brightness of the inner

surface of the large sphere, yields a corresponding $r_{h\lambda}$ and finally by means of Eq. (2) the $\epsilon_{h\lambda}$ sought. An appropriate filter, F, of Christianson or other type, yields the wave-length desired. An averaged spectral brightness for the hemisphere, ${}_1B_{h\lambda}$ is assured by having its image just fill the opening in screen N. Comparisons are made in the standard manner with the auxiliary source S_2. An ordinary optical pyrometer cannot be used

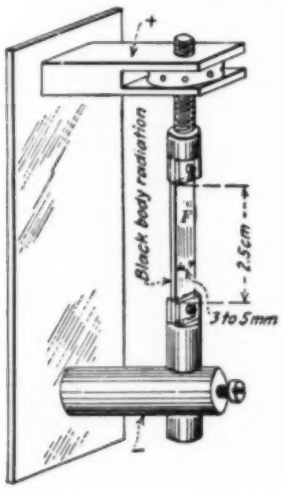


FIG. 5. Mendenhalls open-V, blackbody wedge.

because the hemispherical surface ordinarily will not be uniformly bright. However, a photoelectric cell with a sufficiently large aperture placed back of N may be safely used. A determination of the brightness of the inner surface of the large sphere involves replacing the hemispherical mirror by a plane mirror of known $r_{h\lambda}$ with axis slightly tilted with respect to the photometric axis. The screen opening at N is then completely filled with light reflected from the inner surface of the sphere. A comparison of this image at N of spectral brightness, ${}_2B_{h\lambda}$ with the auxiliary source S_2 is made as before. It follows that

$$\epsilon_{h\lambda}=1-r_{h\lambda}=1-{}_1B_{h\lambda}/{}_2B_{h\lambda}. \qquad (4)$$

The foregoing method has not actually been used so far as the writer knows. Perhaps there has not been sufficient need for the emissivity thus measured. An approximation to this method however, has been used by Prescott and Morrison[32] in a determination of the surface temperature of an oxide-coated filament. Because of the variability of oxide coatings for filaments in practice and because of the low thermal conductivity of the oxide layer, measurements with an optical pyrometer of the temperature of a coated tubular filament with its wall pierced by a small hole are not satisfactory. In place of the sphere, Prescott used a cylindrical tube lined with white fluffy cotton which was lighted up by two automobile headlight lamps at opposite ends of the tube. A lamp with the oxide-coated filament was mounted with filament along the axis of the tube. An optical pyrometer was used to measure the spectral brightnesses (1) of the oxide surface with the headlight lamps unlighted, (2) of the oxide surface with the headlight lamps lighted, and (3) of the cotton lining with the headlight lamps lighted. The further procedure for obtaining an $r_{h\lambda}$ and an $\epsilon_{h\lambda}$ is evident. Strictly the emissivity obtained was neither normal nor hemispherical since the average brightness was for a cylindrical surface.

To obtain in a similar way a hemispherical spectral emissivity wherever desired in the infra-red, using receivers responding to the thermal effects of radiation, would seem quite practicable. Inner surface coverings for the sphere such as a diffusing aluminum paint which are generally highly reflecting and highly diffusing throughout the infra-red, and selectively reflecting materials for filter purposes are both available.

DIRECT BRIGHTNESS AND STERADIANCY COMPARISONS

In accord with the definition of an emissivity, these methods employ direct comparisons of a spectral brightness or a spectral steradiancy of the body (a nonblackbody) with that of a blackbody at the same temperature. Often but not always the material of the nonblackbody also forms that of the blackbody and in such instances the condition of a common temperature for the two bodies is easily attained.

Le Chatlier according to Burgess[b] was the first to use the blackbody characteristic of a cavity in determining the brightness temperature S_λ, true temperature T, relations for a nonblackbody. Since S_λ and T are connected with ϵ_λ by the relation

$$\ln \epsilon_\lambda=\frac{c_2}{\lambda}\left(\frac{1}{T}-\frac{1}{S_\lambda}\right), \qquad (5)$$

a relation such as $S_\lambda = f(T)$ leads at once to ϵ_λ as a function of T.

It was Mendenhall,[26] however, who in 1911 first proposed the open-V wedge device as a practical method for assuring equality of temperature for the black and the nonblackbodies which were to be compared. The procedure was simple and a considerable impetus to the study of high temperature radiations was given thereby. For polished material, as is evident from Fig. 5, the brightness viewed along OA is a composite brightness, being the sum of the natural brightness of A for the direction AO, the natural brightness of B once reflected, that of C twice reflected, that of D three times reflected, that from C directed toward D four times reflected, etc., in all seven terms. In equation form this yields for the spectral brightness of the wedge opening ${}_wB_\lambda$

$$ {}_wB_\lambda = {}_nB_\lambda(1+r_\lambda+r_\lambda^2+\cdots r_\lambda^6), \qquad (6) $$

where ${}_nB_\lambda$ is the natural spectral brightness of the wedge material. Though strictly speaking ${}_nB_\lambda$ varies with the angle of emission, that variation is immaterial here. Were the series of Eq. (6) infinite, the right-hand member would represent the spectral brightness of a blackbody at the temperature of the wedge, ${}_bB_\lambda$. In the case of a 10°-wedge, the departures of the wedge opening from blackness $({}_bB_\lambda - {}_wB_\lambda)/{}_bB_\lambda$ amount, respectively, to 0.0001, 0.0016, 0.018, 0.16 and 0.40 for spectral reflectivities of 0.60, 0.70, 0.80, 0.90 and 0.95. Such a wedge is seen to be suitable for a blackbody, if the spectral reflectivity is of the order of 0.75 or less; and, where such is the case, the spectral emissivity $\epsilon_{n\lambda}$ may be taken as the ratio ${}_nB_\lambda/{}_wB_\lambda$, the ${}_nB_\lambda$ being measured in the direction PQ (Fig. 5). This method was considerably used by Mendenhall and Forsythe,[27] Spence,[34] McCauley[25] and others.

The open-V wedge fails if the surface is not polished, but polishing ordinarily does not represent a serious difficulty. There are certain real difficulties, however. If the wedge is formed from a single sheet of material, a bulge will form on the inside at the sharp edge. If formed from two sheets instead, a slot is quite likely to be produced when the wedge is heated. Both effects are very serious so far as blackbody conditions are concerned.

The best method for obtaining blackbody radiation whose temperature is the same as or very nearly the same as that of the material under study, where the heating is done electrically, seems to be that of shaping the material into a

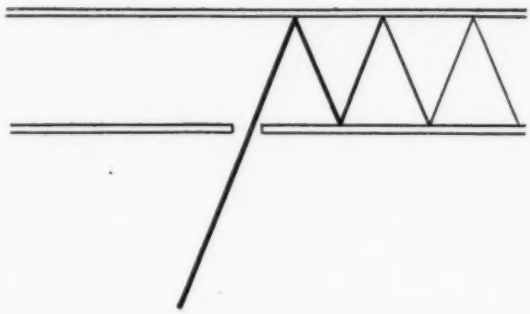


FIG. 6. Diagram showing how radiation through a small hole in the side wall of a uniformly heated tube builds up to form blackbody radiation.

uniform tube with small holes through its sidewall. This was done first by the writer[45] (Fig. 6) in a study of the radiation characteristics of tungsten. In this case the tungsten tube was formed by extruding through an annular die, tungsten powder which had been mixed with a binder. The holes were punctured shortly after the extrusion. The blackening of the radiation for a somewhat slantwise angle of emission from such a hole is nearly complete and independent of the polish which may or may not be present on the inner surface of the tube. If the thermal conductivity of the material is known, correction may be made for the difference in temperature between the internal and external surfaces of the tube wall. An emissivity, obtained by comparing an external surface brightness with that of an adjacent hole, would seem to be free from error of method. In some instances, as for Pt, Pd, Au, and steel, small tubes may be purchased from supply houses. With small holes properly drilled, these tubes are equally as satisfactory as those just described.

The methods described for obtaining tubes with small holes in the sidewalls are not always convenient or possible. In that case, one may use a ribbon with small holes drilled through it, as has been done by Wahlin[39] and his co-workers,[43] and roll it around a mandrel to form a complete tube with opposite edges of the ribbon touching

along a line parallel to the axis of the tube. Such tubes would seem to be nearly if not quite as satisfactory as the tubes which have been described. Still another method of obtaining a tube consists in winding a narrow ribbon, such as may be obtained by rolling down a circular wire, on a mandrel to yield a tightly closed spiral.

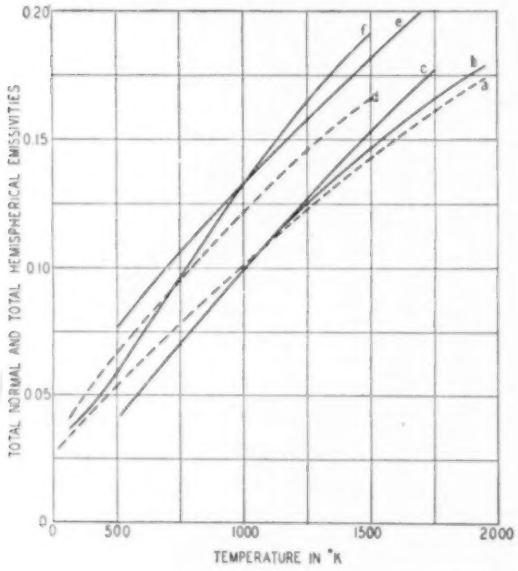


FIG. 7. A composite plot showing total emissivities, normal ϵ_{nt} and hemispherical ϵ_{ht} for platinum; (a) theoretical curve for ϵ_{nt} derived by Foote, reference 11; (b) curve representing average of two sets of observed values of ϵ_{nt} obtained by Foote; (c) curve representing values of ϵ_{nt} obtained by Lummer and Kurlbaum, reference 22b; (d) theoretical curve for ϵ_{ht} derived by Davisson and Weeks, reference 9; (e) curve representing observed values obtained by Geiss, reference 12, and separately by Lummer, reference 22; (f) curve representing observed values obtained by Davisson and Weeks, reference 9.

Previous to the winding, the edges of the wire should be notched slightly to yield the desired holes leading to the interior. This method was used by the writer[46] in a study of the emissivities of Mo. Such blackbody tubes are definitely inferior to those previously described.

When the spectral emissivity of one metallic substance is known, that of a second metallic substance may be obtained by direct comparison. In making such a determination for Ta by comparison with Mo, the writer fused end to end two equally sized filaments, one of Mo and one of Ta, mounted them as a lamp filament, heated them to incandescence, observed their spectral brightnesses as functions of the distances from their junction, extrapolated such brightnesses for short distances to the junction, and computed the emissivities for the tantalum on the basis that the extrapolated spectral brightnesses corresponded to a common temperature. This is not recommended as a primary method because of the alloying action of the metals while being fused as well as afterwards when the junction is at a high temperature. The results obtained for Mo by this method checked well with those obtained otherwise.

Thus far tubular blackbodies have been used chiefly for visual studies probably because of the larger holes in the sidewalls, the larger tube and consequently the larger heating currents that would be demanded for receivers other than the eye.

Spectral emissivities for a material are also obtainable from comparisons of spectral radiancy curves of the substance at a given temperature. Assuring, where incandescent temperatures are concerned, that the two temperatures involved are precisely the same is the main drawback to this method. Could one rely upon the Mendenhall open-V wedge to yield blackbody radiation, as was hoped for by McCauley[25] in his studies, such methods would be highly satisfactory. For temperatures which can be measured and regulated precisely with the aid of thermocouples, the general method is acceptable now.

HEMISPHERICAL SPECTRAL EMISSIVITIES BY AVERAGING

Given for a material at some one temperature, a normal spectral emissivity $\epsilon_{n\lambda}$ and the variation with angle of emission θ for spectral emissivities of the same wave-length $\epsilon_{\theta\lambda}$, one can compute the corresponding hemispherical spectral emissivity $\epsilon_{h\lambda}$. By zonal integration, taking account of the fact that the projection of an element of area varies as cos θ, one obtains

$$\epsilon_{h\lambda} = \frac{\int_0^{\pi/2} \epsilon_{\theta\lambda} 2\pi \sin\theta \cos\theta d\theta}{\int_0^{\pi/2} 2\pi \sin\theta \cos\theta d\theta}. \qquad (7)$$

The first precise measures of variations of $\epsilon_{\theta\lambda}$ with θ, seem to have been made by Bauer and

Moulin[2] in their study of polished platinum. Similar measurements have been made by the writer, on the variations of $\epsilon_{\theta\lambda}$ for tungsten, (Fig. 1) molybdenum, tantalum and carbon. From these studies, it has been found that the ratios of $\epsilon_{h\lambda}/\epsilon_{n\lambda}$ for Pt, W, Mo, Ta, and C in order are *1.045*, *1.044*, *1.062*, *1.042*, and *0.92*. While certain general conclusions seem indicated, the results are really too few in number to justify their statement.

Measurement of Total Emissivities

METHOD OF COMPUTATION BASED ON $\epsilon_\lambda = f(\lambda)$

It is obvious that if $\epsilon_{n\lambda} = f(\lambda)$ is known, one may obtain ϵ_{nt} by the relation

$$\epsilon_{nt} = \frac{\int_0^\infty \epsilon_{n\lambda}\lambda^{-5}(e^{c_2/\lambda T}-1)d\lambda}{\int_0^\infty \lambda^{-5}(e^{c_2/\lambda T}-1)d\lambda}. \quad (8)$$

It is equally obvious that, if $\epsilon_{h\lambda} = f(\lambda)$ is known, one may obtain ϵ_{ht} in an exactly similar manner.

Drude, assuming Maxwell's electromagnetic theory, deduced the well-known relation

$$\epsilon_{n\lambda} = 1 - r_{n\lambda} = A_1(\rho/\lambda)^{\frac{1}{2}}, \quad (9)$$

where ρ is the resistivity of the material and A_1 a constant having the value 0.365 ohm$^{-\frac{1}{2}}$. Using this relation, Aschkinass[1] derived for the total emissivity of a metal the relation

$$\epsilon_{nt} = A_2(\rho T)^{\frac{1}{2}}. \quad (10)$$

This equation was tested for platinum by Lummer[22] and by Weber.[41] Deviations were assumed as due to the failure of the theoretical relations to take account of the variation of platinum from the Lambert cosine law.

In 1915 Foote,[11] using the more accurate radiation constants then available, extended Aschkinass' relation to include the second-order approximation term. He obtained for platinum

$$\epsilon_{nt} = A_3(T\rho)^{\frac{1}{2}} - A_4(T\rho), \quad (11)$$

A_3 and A_4 having the values 0.5736 (ohm cm K°)$^{-\frac{1}{2}}$ and 0.1769 ohm cm K°. In the region 1000°K to 1500°K where measurements were made the predicted values were generally slightly too low.

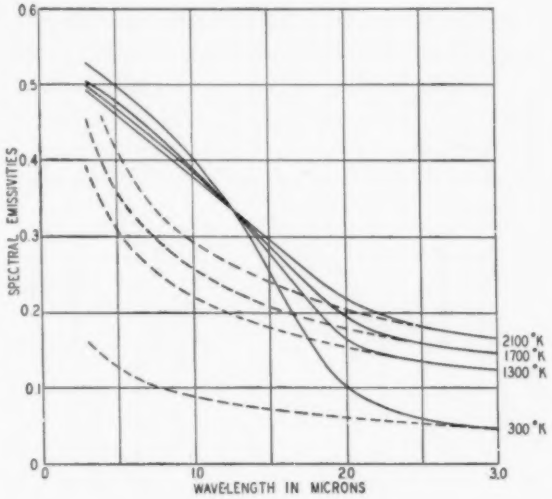


FIG. 8. Observed normal spectral emissivities for tungsten as a function of wave-length for several temperatures, and expected variations (···) as a function of wave-length were the Drude relation general.

Still later Davisson and Weeks[9] taking account of the variation in $\epsilon_{\theta\lambda}$, expected in accord with electromagnetic theory, arrived at the following expression for the ϵ_{ht} for platinum

$$\epsilon_{ht} = 0.8992\ \text{ohm}^{-\frac{1}{2}}\left(\frac{T\rho}{c_2}\right)^{\frac{1}{2}} - 0.9047\ \text{ohm}^{-1}\left(\frac{T\rho}{c_2}\right) + 1.149\ \text{ohm}^{-\frac{1}{2}}\left(\frac{T\rho}{c_2}\right)^{\frac{1}{2}} - 1.245\ \text{ohm}^{-2}\left(\frac{T\rho}{c_2}\right), \quad (12)$$

of which c_2 is the second radiation constant for which 1.432 cm K° was accepted. As shown in Fig. 7, computed values for ϵ_{ht} for platinum are greater than the observed values for temperatures below 700°K, and less for temperatures above 700°K, the difference increasing with increase in temperature. Fig. 7 also shows that both the computed and observed values for ϵ_{ht} are greater than the corresponding ϵ_{nt}. Davisson and Weeks concluded that the deviation between computed and observed results at the higher temperatures could readily be explained by the well-known failure of the Drude relation in the region of the near infra-red the visible and the ultraviolet, evidence for which is shown in the observations for tungsten (Fig. 8).

Filament in Vacuum Method

This method of measuring $\epsilon_{\lambda t}$ is particularly applicable to metals which can be mounted and heated as incandescent lamp filaments in vacuum. It is also applicable to substances which, in the form of thin opaque coatings, can be applied to such filaments. Temperature measurements in such instances represent the greatest sources of uncertainty.

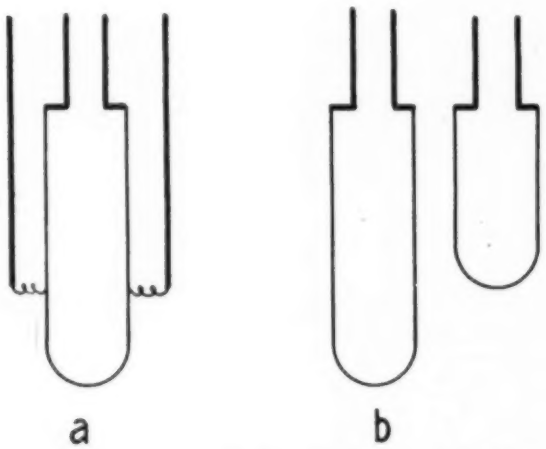


Fig. 9. Showing (a) a single filament mount with potential leads and (b) a two-filament mount with filaments of different lengths, for use in the filament-in-vacuum method of measuring $\epsilon_{\lambda t}$.

The filament-in-vacuum method requires, for the particular temperatures concerned, that one shall be able to associate a definite heating current, and a definite potential drop with a definite length of filament whose known temperature from one end to the other is sensibly uniform. Two methods of mounting filaments for this purpose are shown in Fig. 9. In the method shown at (a), the portion of the filament chosen is that between the places of attachment of the fine potential leads. In the method shown at (b), the central portion of the longer filament is so chosen. Its length is the difference between those of the two filaments. The potential drop used is the difference between the two drops for the filaments taken separately. One has always to assure one's self by some means that the filaments are sufficiently long so that uniformity of temperature may be secured for the central portion of the longer filament.

Given a filament of length l, of circular cross section of radius r, maintained at a uniform temperature T, by energy supplied electrically at the rate IV in an evacuated space whose dimensions are large in comparison with r and whose boundaries are at the temperature T_0, one can determine an $\epsilon_{\lambda t}$ for the filament material at the temperature T. The condition of a steady state yields

$$IV/2\pi rl+a_{\lambda t}'\sigma T_0^4=\epsilon_{\lambda t}\sigma T^4.$$

In order the terms represent, per unit of surface area of the filament, the rate of supply of energy to the filament electrically, the rate of supply of energy to the filament by absorption of radiant energy incident on its surface, and the rate of emission of radiant energy from the surface of the filament. It is often assumed that $a_{\lambda t}'$ is equal to $\epsilon_{\lambda t}$, but such is not the case. The radiant energy incident, since T_0 the temperature of the surroundings will be different from T, will have a different spectral distribution from that characteristic of a blackbody at temperature T. However, if T differs but little from T_0, one may assume equality and solve for an approximate $\epsilon_{\lambda t}$ which later may be adjusted if additional determinations at other neighboring temperatures show that such is necessary. If, on the other hand, T is considerably in excess of T_0, the term containing $a_{\lambda t}'$ tends to become negligibly small and a precise value for it becomes unnecessary. In many instances that term may be neglected altogether. Generally for metals, if not always, the $a_{\lambda t}'$ will be less than the $\epsilon_{\lambda t}$ for any particular case.

The foregoing method has been used considerably in determining hemispherical total emissivities of metals through wide ranges of temperature. Corresponding emittances of bodies, whose surfaces are not polished or whose partially transparent surface layers differ from the underlying layers, may be determined by this method.

Total Radiation Pyrometer Method

There are various forms of total radiation pyrometers. Which one is used is not material here. For this work, however, it is essential that the calibration of the instrument shall show directly or through computation the instrument response as a function of the net rate of receipt of radiant energy. If the temperature of the

surroundings T_0 is uniform, this net rate is $k(\epsilon_t\sigma T^4-\sigma T_0^4)$, of which σ is the Boltzmann radiation constant and k a constant depending on the detailed dimensions of the set-up.

To obtain the ϵ_{nt} of some material at some specified temperature T, one needs first to expose the pyrometer to the radiation from a properly prepared body of that material held at the temperature T. The body should be opaque, have a plane polished surface oriented with its normal directed toward the pyrometer, and in size be such as to fill completely the opening in a radiation-limiting disk which is fixed with respect to the pyrometer. The instrument response d, possibly a galvanometer deflection, is noted. Next with conditions in all respects the same, except that a blackbody also at temperature T replaces the body whose ϵ_{nt} is desired, a corresponding response d_0 is noted. In accord with the above given expression for the net rate of reception of radiant energy, it follows that

$$\frac{d}{d_0}=\frac{\epsilon_t\sigma T^4-\sigma T_0^4}{\sigma T^4-\sigma T_0^4} \tag{13}$$

and that

$$\epsilon_t=\frac{d}{d_0}+\left(1-\frac{d}{d_0}\right)\left(\frac{T_0}{T}\right)^4. \tag{14}$$

In case (T_0/T) is small compared with one or d/d_0 approximately equals one, the ratio d/d_0 may be taken as the total emissivity. If the solid angle subtended at the receiving element of the pyrometer by the aperture of the limiting disk is small, the observed ϵ_t is an ϵ_{nt}. If the solid angle is approximately hemispherical, it becomes an ϵ_{ht}. Emittances are measured by this method as well as emissivities. In industry normal total emittances are very often measured.

Method of Total Reflection

This method does not seem to have been used, though it possesses certain features tending toward precision. As shown in Fig. 10, the material under study is shaped as a hemisphere, water cooled to a temperature T_0, and mounted at the center of a large sphere kept at a higher temperature T. A concave mirror outside, receiving radiation from the hemisphere through a small hole in the large sphere, serves to focus the whole of the hemisphere and no more onto the blackened disk of a thermocouple receiver or a total radiation pyrometer. By a slight shift of the hemisphere sidewise, the mirror, in effect, will image instead a portion of the wall on the total radiation receiver.

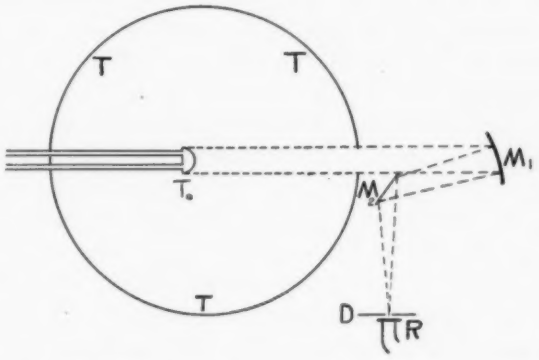


Fig. 10. Diagram of apparatus for the measurement of hemispherical total emissivities at low temperatures using the method of total reflection.

If the receiver and its surroundings are also at temperature T_0 and if the reflectance of the hemisphere for blackbody radiation characterized by the temperature T is sensibly the same as for blackbody radiation characterized by temperature T_0, it may be shown that

$$r_{ht}=\frac{(1-\epsilon_{ht})T^4-T_0^4+\epsilon_{ht}T_0^4}{T^4-T_0^4}=1-\epsilon_{ht}=\frac{d}{d_0}, \tag{15}$$

where d is the receiver response for the condition where the hemisphere is centrally located and d_0 that for the condition where the hemisphere is somewhat displaced. It has been tacitly assumed that the reflectivity of the concave mirror and the absorptivity of the receiver are both unity. However, taking into account the deviations therefrom in no way affects the equality between the first and the last members of (15).

Parallel Plate Method

This method described recently by the writer[48] is based on the proposition that the rate of transfer of energy by radiation between two parallel plates is a function of their hemispherical total emissivities It seems not to have been used for actual measurements though the underlying equations are well known and have been con-

siderably used in industry. In an opaque-walled box (Fig. 11) held at temperature T_0 and with dimensions large in comparison with those of the contained device, there is mounted an electrically heated metal plate A with surface kept at a temperature T' as determined by thermocouples. Let its surface have a known hemispherical total emissivity, ϵ_{ht} which is preferably high and a reflectivity which is as nearly perfectly diffuse as possible. Near to this plate and parallel to it on one side, there is mounted a smaller circular plate B with one surface covered with the material to be studied and protected by a guard ring. The mass, the dimensions, and the specific heat of plate B must be known. The temperature of its surface as well as that of the guard ring must be measurable, preferably by a resistance thermometer or a thermocouple. The space between the plates and presumably inside the box should be evacuated.

The procedure follows. Initially by means of a cooling device not shown in the figure, plate B is brought to a temperature lower than T_0 while plate A is maintained at temperature T'. Then with the cooling device removed, one observes the temperature T of plate B as a function of time. From a plot of such data, one is able to determine the time rate $(dT/dt)_0$ at the instant that T becomes T_0. From this, the mass of the plate, its specific heat, and the area presented toward plate A, one determines the net rate of transfer per unit of area, of energy from plate A at T to plate B at T_0 by radiation. Call this rate W. Consideration of the various processes of emission, absorption and reflection between plates A and B for the above specified characteristics for the surface of A, together with the assumption that the absorptance of B for the radiant energy incident on the A side is essentially equal to its emissivity—this would be very nearly true if T' differs but little from T_0—leads to the relations

$$W=\frac{1}{1/_1\epsilon_{ht}+1/_2\epsilon_{ht}-1}(\sigma T^4-\sigma T_0^4) \qquad (16)$$

and to

$$1/_2\epsilon_{ht}=\frac{\sigma(T^4-T_0^4)}{W}-1/_1\epsilon_{ht}+1. \qquad (17)$$

All of the terms on the right-hand side of the equation are directly measurable. If precise measurements for the hemispherical total emissivity of a material of the corresponding emittance of a body in industry is desired the above would seem to be a fairly simple and precise method for the determinations.

The factor

$$\frac{1}{1/_1\epsilon_{ht}+1/_2\epsilon_{ht}-1}$$

is used in industrial calculations for the transfer of radiant energy between surfaces. McAdams[24] refers to it as an "emissivity factor."

Luminous Emissivity

This term has often been called visible emissivity. It applies to luminous radiations and can have significance only for materials raised to incandescence. An ϵ_l may obviously be obtained (1) by comparing with a photometer the brightness of the material at some temperature with that for a blackbody at the same temperature.

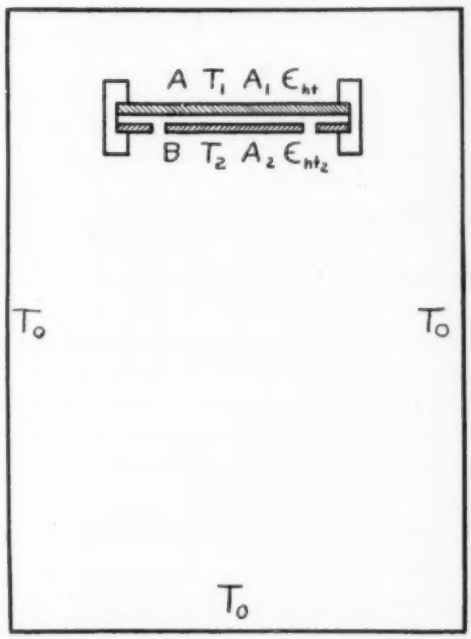


FIG. 11. Diagram of apparatus for the parallel plate method of measuring hemispherical total emissivities.

The ratio of the two brightnesses is the ϵ_l sought. An ϵ_l may also be obtained (2) by computations based on known measured values of ϵ_λ. The formula is

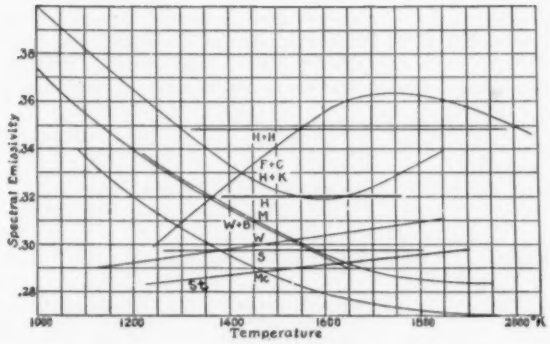
$$\epsilon_l = \frac{\int_0^\infty \epsilon_\lambda L_\lambda \lambda^{-5}(e^{c_2/\lambda T}-1)^{-1}d\lambda}{\int_0^\infty L_\lambda \lambda^{-5}(e^{c_2/\lambda T}-1)^{-1}d\lambda}, \quad (18)$$

where L_λ is the spectral luminosity or luminosity factor of radiation. Evidently an ϵ_l is a weighted average of ϵ_λ's. To the writer's knowledge luminous emissivities have been determined only for such substances as tungsten, tantalum, and molybdenum.

Color Emissivity

Like luminous emissivity, this term can have significance only for materials at incandescence, and then only when their radiations may be color matched with those from a blackbody at some temperature. Strictly speaking an ϵ_c is not an emissivity at all, since radiations for the material at one temperature are compared with those for a blackbody at another temperature. It is, however, a convenient term. An ϵ_c may obviously be obtained (1) by comparing with a photometer the brightness of the material at some temperature with that of a blackbody at a temperature such that its color matches the material being studied. An ϵ_c may also be obtained (2) with the aid of an optical pyrometer whose color filter can be changed so as to yield at one time an effective wave-length λ_r, in the red, say, and at another time as desired an effective wave-length λ_b, in the blue, say. When obtaining the ϵ_c for a given material at a temperature T, one seeks for a blackbody at temperature T_c whose spectral brightness in the red bears to the corresponding spectral brightness for the material a ratio which is exactly the same as that for the blue light. This ratio is the ϵ_c sought. An ϵ_c may also be obtained (3) by computations based on known spectral emissivities for two wave-lengths in the visible say $\epsilon_{\lambda r}$ and $\epsilon_{\lambda b}$ for wave-lengths λ_r and λ_b. For this computation, it is customary to substitute the Wien spectral radiancy equation for the Planck equation. For most practical cases the error is very small. By definition

$$\epsilon_c = \frac{\epsilon_\lambda e^{-c_2/\lambda T}}{e^{-c_2/\lambda T_c}} = \epsilon_\lambda e^{-(c_2/\lambda)(1/T-1/T_c)} = \text{const.} \quad (19)$$



Curve	Author	Year	λ
H and *K*	Holborn and Kurlbaum[17]	1903	0.65μ
W and *B*	Waidner and Burgess[40]	1907	.66
L and *M*	Laue and Martens[20]	1907	.63
F and *C*	Fery and Cheneveau[10]	1909	.629
H	Henning[14]	1910	.665*
M	Mendenhall[26]	1911	.658
Mc	McCauley[25]	1913	.658
S	Spence[34]	1913	.658
H and *H*	Henning and Heuse[15]	1923	.647
W	Worthing[47]	1925	.665
St	Stephens[35]	1939	.665

* Interpolated from results for 0.680μ and 0.627μ.

FIG. 12. Published spectral emissivities of platinum for red light at incandescent temperatures as obtained by various experimenters.

The constant must not vary with the wave-length in the visible region. Choosing two wave-lengths λ_r and λ_b, we may write therefore

$$\epsilon_{\lambda r} e^{-(c_2/\lambda_r)(1/T-1/T_c)} = \epsilon_{\lambda b} e^{-(c_2/\lambda_b)(1/T-1/T_c)} \quad (20)$$

or

$$\ln \frac{\epsilon_{\lambda r}}{\epsilon_{\lambda b}} = c_2(1/T-1/T_c)(1/\lambda_r - 1/\lambda_b). \quad (21)$$

For tungsten at 2500°K, 0.665μ and 0.467μ as selected values for λ_r and λ_b, and 0.425 and 0.462 as the corresponding $\epsilon_{\lambda r}$ and $\epsilon_{\lambda b}$, we obtain with the aid of Eq. (19), 2557°K as T_c, and with the aid of Eq. (19), 0.356 as ϵ_c. Color emissivities have been determined mainly for metals such as tungsten, molybdenum, and tantalum in the field of illumination.

Measurement of Emittances

It is obvious that emittances are measured by exactly the same methods as are emissivities. There is the exception that the reflectivity methods are applicable only when the body whose emittance is being sought is opaque. This is in accord with the fact that, when the body is opaque, has a polished surface and is composed of a single material, an emittance of the body is the corresponding emissivity of the material.

TABLE I. *Normal spectral emissivities for metallic elements and alloys at temperatures generally above 1000°K. Room temperature values are given in a few instances where they, along with values at higher temperatures, form a connected series and where the values given for the higher temperatures depend on those given for low temperatures.**

Author	Method	T in °K	Red λ in μ, $\epsilon_{n\lambda}$		Green λ in μ, $\epsilon_{n\lambda}$		Blue λ in μ, $\epsilon_{n\lambda}$		IR and UV λ in μ, $\epsilon_{n\lambda}$		Remarks
					Carbon						
Prescott and Hincke[31]	Tube	1600	0.66	0.89							
		2500	0.66	0.84							
					Columbium						
Whitney[43]	Tube	1600–2500	0.66	0.374							Highly Outgassed
					Copper						
Stubbs[36]	Spectrophotometer		0.66	0.11							Solid
	Spectrophotometer		0.66	0.15							Liquid
Bidwell[3]	Couple and pyrometer	900–2100	0.66	0.105							Solid and liquid
Burgess and Waltenberg[6]	Contact with Pt	1275	0.66	0.105							Solid
		1350	0.66	0.120	0.55	0.38					Solid
		1375	0.66	0.15	0.55	0.36					Liquid
Burgess[4]	pyrometer	1450	0.66	0.14	0.55	0.32					Liquid
	pyrometer	1500	0.66	0.13	0.55	0.28					Liquid
					Gold						
Holborn and Henning[16]			0.66	0.127							
Stubbs and Prideaux[37]	Spectrophotometer	<1336	0.665	0.120	0.535	0.410	0.495	0.531			Solid
	Spectrophotometer	>1336		0.208		0.405		0.473			Liquid
Bidwell[3]	Couple and pyrometer	1100–2020	0.66	0.125							Solid and Liquid
Burgess and Waltenberg[6]	Contact with Pt	1275	0.650	0.145	0.550	0.38					Solid
	Contact with Pt	>1336	0.650	0.219	0.550	0.38					Liquid
Worthing[47]	Tube, reflectivity	1275	0.665	0.140	0.535	0.448	0.460	0.632			Solid
					Iron						
Bidwell[3]	Couple and pyrometer	1000	0.66	0.27							Solid
		1480–1500	0.66	0.29							Solid and liquid
Burgess and Waltenberg[6]	Contact with Pt	1480–1500	0.65	0.37							Solid and liquid
					Konal						
Millis[28]	Pyrometer	1200	0.665	0.43							
					Molybdenum						
Mendenhall and Forsythe[27]	Open-V wedge	1300	0.658	0.44							
		2000		0.38							
		2750		0.39							
Burgess and Waltenberg[6]		2300	0.650	0.43							
Worthing[46]	tube, reflectivity, contact with tungsten	300	0.665	0.420			0.467	0.425			
		1300		0.378				0.395			
		2000		0.353				0.380			
		2750		0.332				0.365			
Whitney[43]	tube	1300–2100	0.667	0.382							Highly outgassed
					Nickel						
Henning[14]	Reflection										
Bidwell[3]	Couple and pyrometer	1200	0.660	0.250							Solid
		1700	0.660	0.215							Solid
			0.660	0.215							Liquid
Burgess and Waltenberg[6]	Contact with Pt	1200–1700	0.66	0.36	0.55	0.44					Solid
			0.66	0.37	0.55	0.46					Liquid
Worthing[47]		1200–1650	0.665	0.375	0.535	0.425	0.460	0.450			Solid
					Palladium						
Waidner and Burgess[40]		1275	0.66	0.35							
		1725		0.31							
Burgess and Waltenberg[6]	Contact with Pt	1805	0.650	0.33	0.55	0.38					Solid
		1830		0.37							Liquid

* For many recommended emissivities see Int. Crit. Tab. **5**, 242.

When the surface of a body is polished, there is no doubt as to how one shall determine the surface area that enters into radiancy and steradiancy measurements and hence into emissivity and emittance determinations. What shall be done in the case of roughened surfaces is not so obvious. The general rule seems to be that when the roughened dimensions are small compared with distances to the receiving instruments and its dimensions, the area that is taken as source area is a projected smooth area which follows the general outline of the body. This is the case which is generally of importance. For opaque bodies, of some one material, the emittances in such cases are never less than, but instead always greater than the corresponding emissivities of the material. In some instances, as in the case of projection lamps containing crimped or zigzag-shaped ribbon filaments of tungsten, advantage is taken of this principle to attain an emittance considerably in excess of the emissivity of the tungsten.

How the normal total emittance ϵ_{nt}' of a polished piece of copper is changed in the region

TABLE I.—*Continued.*

AUTHOR	METHOD	T IN °K	RED λ IN μ, $\epsilon_{n\lambda}$		GREEN λ IN μ, $\epsilon_{n\lambda}$		BLUE λ IN μ, $\epsilon_{n\lambda}$		IR AND UV λ IN μ, $\epsilon_{n\lambda}$		REMARKS
						Platinum (See Fig. 12)					
						Rhodium					
Whitney[42]	Tube	1300–2000	0.667	0.242							Highly outgassed
						Silver					
Henning[14]	Spectropyrometer		0.66	0.077							
Bidwell[5]	Couple and pyrometer	1000–1700	0.66	0.055							Solid and liquid
Burgess and Waltenberg[6]	Contact with Pt	1215	0.650	0.044							Solid
		1255		0.072							Liquid
Stubbs[38]	Spectrophotometer		0.66	0.072							Liquid
						Tantalum					
Mendenhall and Forsythe[27]	Open-V wedge	1400	0.658	0.61							
		2100		0.49							
		2800		0.47							
McCauley[25]	Spectrobolometer	1400	0.658	0.59							
		2100		0.47							
		2800		0.46							
Worthing[47]	Reflectivity, tube, contact with W and Mo	300	0.665	0.493			0.467	0.565			
		1400		0.442				0.505			
		2100		0.415				0.460			
		2800		0.390							
Utterbach and Sanderman[39]	Open-V wedge	1400	0.667	0.49							
		2100		0.40							
Malter and Langmuir[25]	Tube	1200	0.665	0.459							
		2100		0.417							
		2800		0.394							
						Thorium					
Whitney[42]	Tube	1300–2000	0.667	0.380							Highly outgassed
						Tungsten					
Pirani[29]	Open-V wedge	1200	0.64	0.46							
		1700		0.48							
Mendenhall and Forsythe[27]	Open-V wedge	1375	0.658	0.45							
		3175		0.66							Obviously in error
Burgess and Waltenberg[6]	Contact with Pt	2044	0.65	0.39							
Pirani and Meyer[30]	Helix				0.532	0.44					
Langmuir[19]	Helix	1400–3000	0.664	0.46	0.537	0.485					Large variations
Shackelford[33]	Helix	1900	0.656	0.456			0.493	0.470			
	Helix	2300		0.445				0.465			
Hulburt[13]	Photoelectric comp.	1800			0.54	0.452	0.46	0.488	0.34	0.501	
		2200				0.438		0.476		0.496	
		2800				0.424		0.465		0.492	
Worthing[46]	Tube	300	0.665	0.470			0.467	0.505			
		1200		0.452				0.482			
		2200		0.431				0.466			
		3200		0.411				0.452			
Weniger and Pfund[42] and Coblentz[7]	Spectrobolometer Reflectivity	300							1.27	0.335	2.00 0.100 2.50 0.062
		1300								0.335	0.162 0.129
		1700								0.335	0.187 0.155
		2100								0.335	0.212 0.179
Henning and Heuse[15]	Cavity in sphere	2000–3200	0.647	0.49	0.536	0.49					5% uncertainty
Lax and Pirani[21]	Tube		0.650	0.45							
Zwikker[49]											
Hamaker[12]	Reflectivity	300	0.650	0.453	0.550	0.469	0.450	0.492	0.230	0.423	0.300 0.505 0.350 0.476 0.800 0.466 1.000 0.424
		1200		0.444		0.458		0.477		0.411	.493 .471 .434 .388
		2000		0.436		0.448		0.463		0.400	.483 0.467 .405 .355
Wahlin and Whitney[39]	Tube	1200–2200	0.669	0.46							Highly outgassed

of low temperatures by the addition of thin coats of lacquer, by tarnishing and by painting with aluminum is shown by certain results obtained by Heilman[13b] (Fig. 13). For the temperatures involved, it is obvious, (a) that polished copper has very low total emissivities, (b) that tarnished copper has much higher emittances than has polished copper (the increase in the very bright new copper curve in going from 300°F to 500°F is undoubtedly due to the appearance of tarnish), (c) that the total emissivities of polished aluminum are greater than those for copper, (d) that the total emittances of unpolished aluminum are greater than the corresponding emissivities, (e) that the thin coats of lacquer were not opaque, and (f) that the white lacquer when opaque is nearly black.

Emissivity Results

SPECTRAL EMISSIVITIES

Spectral emissivities for various materials mostly metals are shown in Table I. Except for a few cases where a room temperature value has been one of a group showing $\epsilon_\lambda = f(T)$, the room temperature values have been omitted. A survey of results, including much that is not in Table I,

seem to point toward certain general tendencies though the data are too meager really to make sure in certain cases. As such tendencies we

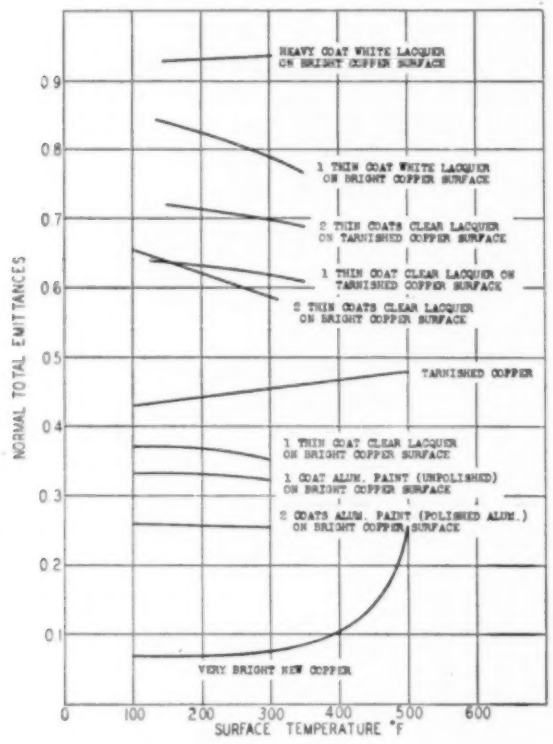


FIG. 13. Normal total emittances at low temperatures for pieces of bright newly polished copper when uncoated and when variously coated, as determined by R. H. Heilman, reference 13b.

seem to have:

(1) The Drude spectral emissivity relation $\epsilon_{\lambda n} = A(\rho/\lambda)^{\frac{1}{2}}$ (Eq. (9)) where ρ stands for resistivity, holds well for metals at wave-lengths beyond a rather indefinite "Drude limit" in the near infra-red. (See Fig. 8.)

(2) Spectral emissivities for metals on the short wave-length side of the "Drude limit" increase with decrease in wave-length to a maximum generally in the ultraviolet. (See Fig. 8.)

(3) Spectral emissivities for metals that are not highly outgassed seem at least in certain regions on the short wave-length side of the "Drude limit" to decrease with increase of temperature. (See Table I.)

(4) Spectral emissivities of highly outgassed metals seem not to vary with temperature in the visible region. (See Table I.)

(5) Spectral emissivities obtained using the tubular filament method are generally lower than those obtained by other methods. (See Table I.)

(6) On account of deviations from the Lambert cosine law, hemispherical emissivities for metals are generally greater than corresponding normal emissivities. (See Fig. 1.)

(7) On account of deviations from the Lambert cosine law, hemispherical spectral emissivities for the semi-conductor carbon is less than for the corresponding normal spectral emissivity.

Total emissivities for various materials, as reported by Professor Hottel of Massachusetts Institute of Technology, are to be found elsewhere.[24]

There also seem to be certain general tendencies with respect to the total emissivities. Some of them are:

(1) The total emissivities of metals increase with temperature.

(2) The total emissivities of metals seem to be less than those of nonmetals.

(3) The total emissivities of certain nonmetals decrease with increase of temperature. (See Fig. 14.)

(4) The total emissivities of metals are generally greater than what would be expected were they to obey the Drude law. (See Fig. 8.)

(5) The appearance of a nonmetal in visible light is no guide as to its probable total emissivity. (See Figs. 13 and 14.)

(6) The total hemispherical emissivities of metals on account of deviations from Lambert's law are greater than the total normal emissivities. (See Fig. 2.)

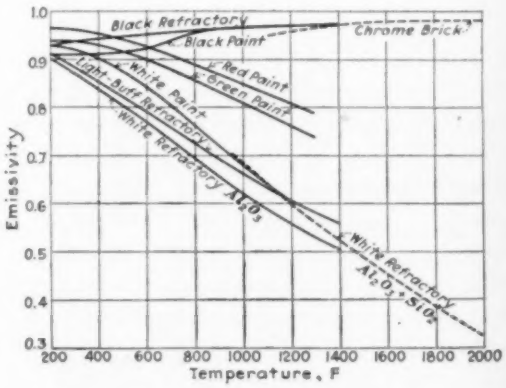


FIG. 14. Some total emittances reported by R. H. Heilman, reference 13a.

Bibliography

1. Aschkinass, Ann. d. Physik **17**, 960 (1905).
2. Bauer and Moulin, J. de phys. et rad. **9**, 468 (1910).
3. Bidwell, Phys. Rev. **3**, 439 (1914).
4. Burgess, Bull. Nat. Bur. Stand. **6**, 111 (1909).
5. Burgess, Comment made at the 1919 Temperature Symposium.
6. Burgess and Waltenberg, Bull. Nat. Bur. Stand. **11**, 591 (1915).
7. Coblentz, Bull. Nat. Bur. Stand. **14**, 312 (1918).
8. Committee on Radiation, Rev. Sci. Inst. **7**, 322 (1936).
9. Davisson and Weeks, J. Opt. Soc. Am. and Rev. Sci. Inst. **8**, 581 (1924).
10. Fery and Cheneveau, Comptes rendus **148**, 401 (1909).
11. Foote, Bull. Nat. Bur. Stand. **11**, 607 (1915).
12. Geiss, Physica **5**, 203 (1925).
13. Hamaker, Doctor's Thesis; Univ. of Utrecht, Holland (1934).
13a. Heilman, Trans. Am. Inst. Chem. Eng. **31**, 165 (1934) plus additional material.
13b. Heilman, Heating Piping Air Cond. **5**, 458 (1933).
14. Henning, Zeits. f. Instrumentenk. **30**, 61 (1910).
15. Henning and Heuse, Zeits. f. Physik **16**, 63 (1923).
16. Holborn and Henning, Berl. Ber. **12**, 311 (1905).
17. Holborn and Kurlbaum, Ann. d. Physik **10**, 225 (1903).
18. Hulburt, Astrophys. J. **45**, 149 (1917).
19. I. Langmuir, Phys. Rev. **6**, 138 (1915); **7**, 302 (1916).
20. Laue and Martens, Physik. Zeits. **8**, 853 (1907).
21. Lax and Pirani, Zeits. f. Physik **22**, 273 (1924).
22. Lummer, E. T. Z. **34**, 1428 (1913).
22a. Lummer, *Verflussigung der Kohle*, (1914), p. 42.
22b. Lummer and Kurlbaum, Verh. Deut. Phys. Ges. **17**, 106 (1898).
23. Malter and D. Langmuir, Phys. Rev. **55**, 743 (1939).
24. McAdams, *Heat Transmission* (McGraw Hill, 1933), Chapter III.
25. McCauley, Astrophys. J. **37**, 164 (1913).
26. Mendenhall, Astrophys. J. **33**, 91 (1911).
27. Mendenhall and Forsythe, Astrophys. J. **37**, 38 (1915).
28. Millis, Master's Thesis, University of Pittsburgh (1933).
28a. Ornstein, Physica **3**, 561 (1936).
29. Pirani, Physik. Zeits. **13**, 753 (1912).
30. Pirani and Meyer, Elektr. u. Masch. **33**, 397 and 414 (1915).
31. Prescott and Hinke, Phys. Rev. **31**, 130 (1928).
32. Prescott and Morrison, Rev. Sci. Inst. **10**, 36 (1939).
33. Shackelford, Phys. Rev. **8**, 470 (1916).
34. Spence, Astrophys. J. **37**, 194 (1913).
35. Stephens, J. Opt. Soc. Am. **29**, 158 (1939).
36. Stubbs, Proc. Roy. Soc. **A88**, 195 (1913).
37. Stubbs and Prideaux, Proc. Roy. Soc. **A87**, 451 (1912).
38. Utterbach and Sanderman, Phys. Rev. **39**, 1008 (1932).
39. Wahlin and Whitney, Phys. Rev. **50**, 735 (1936).
40. Waidner and Burgess, Bull. Nat. Bur. Stand. **3**, 163 (1907).
41. Weber, Ann. d. Physik **54**, 165 (1918).
42. Weniger and Pfund, Phys. Rev. **14**, 427 (1919).
43. Whitney, Phys. Rev. **48**, 458 (1935).
44. Worthing, Astrophys. J. **36**, 345 (1912); J. Opt. Soc. Am. and Rev. Sci. Inst. **13**, 635 (1926).
45. Worthing, Phys. Rev. **10**, 377 (1917) and Zeits. f. Physik **22**, 9 (1924).
46. Worthing, Phys. Rev. **25**, 846 (1925).
47. Worthing, Phys. Rev. **28**, 174 (1926).
48. Worthing, J. Opt. Soc. Am. **30**, 91 (1940).
49. Zwikker, Proc. K. Akad. Amsterdam **28**, 499 (1925).

Special Issue on Temperature

A word of appreciation is due to many who have contributed to the preparation of this issue. The principal papers have been taken from the Symposium on Temperature, sponsored by the American Institute of Physics in New York, November 2–4. The success of that Symposium was due primarily to the work of the members of the Program Committee, and particularly to that of the Chairman, Dr. C. O. Fairchild. Dr. W. E. Forsythe, our Associate Editor, was of great assistance in choosing the papers to appear in this issue. Finally, we express our appreciation to a large number of manufacturers who have contributed information for the Directory of Commercial Temperature-Measuring Equipment.

The Mechanism of Spark Discharge in Air at Atmospheric Pressure. I

BY LEONARD B. LOEB AND JOHN M. MEEK

Department of Physics, University of California, Berkeley, California

The Townsend equation for the passage of a spark is analyzed and its inadequacy for explaining sparks in air at near atmospheric pressures is demonstrated. The mechanisms active in air at higher pressures, *viz.*, the electron avalanche and its tip field, photo-ionization in the gas and positive streamer formation are presented. A quantitative criterion for streamer formation is applied to give a quantitative theory for spark breakdown in air at atmospheric pressures. The theory gives quantitative agreement with experiment and predicts departures from Paschen's law. At values of the product, pressure times gap length less than 200 mm×cm in air, the new mechanism is unimportant. The theory is applied to longer sparks at atmospheric pressures and the effect of the decrease in density of photo-ionization in longer avalanches considered. This leads to a modification of the Meek mechanism by which the electron avalanche slows down while a retrograde positive streamer moves at high speed to the cathode and then advances again. This mechanism enables one to discuss the breakdown potentials of unsymmetrical gaps showing the difference in sparking potential between positive and negative points. The mechanism is correlated with the passage of lightning discharges. Alterations of Meek's theory of the stepped leader are indicated. Part I describes the classical theory of spark discharge and the nature of the mechanism which must be active at higher pressures. Part II will consider streamer formation and spark breakdown in short and long gaps.

1. Classical Theory of Spark Discharge

J. S. TOWNSEND[1] studied the increase of a photoelectric current from the cathode in a plane parallel gap at high electrical fields as a function of field strength and pressure. He worked with short gaps and at low pressures. He was able to show that the current i observed for a given initial photoelectric current i_0 is given by an equation of the form

$$i = i_0 \frac{e^{\alpha x}}{1-\gamma(e^{\alpha x}-1)}.$$

His original equation was slightly different and was based on a coefficient β representing the number of ions created per cm path in the field direction by positive ion impacts on molecules, a process now known to be highly improbable.[2] The present equation is a later alternative independently developed by Townsend and Thomson.[3] In this equation α represents the number of ions per cm path in the field direction created by an electron and γ the number of secondary electrons created by a positive ion at the cathode by any one of a number of different mechanisms, and x is the gap length. As $e^{\alpha x}$ is usually very much greater than 1, the -1 in the denominator may be neglected. Townsend then noted that when the denominator vanishes, i becomes indefinitely great no matter how small i_0. Hence the condition for the spark is

$$1 = \gamma e^{\alpha\delta},$$

where δ is the length of the spark gap. Since both γ and α/p are functions of X/p, the ratio of field strength to pressure; and as $X_s\delta$, in a uniform field for sparking X_s, equals the sparking potential V_s, the sparking potential can be computed from α/p, γ and δ. In many gases at low pressures it was in fact found that the value of V_s could be computed fairly satisfactorily from these quantities *as long as* $p\delta$ lay below $\sim$500 mm Hg×cm.[4] Above this, values of γ could not be measured as sparks occurred before measurable values of γ were achieved. The cause of this failure to observe γ was formerly ascribed to inadequate technique. This is really not the

case, and the masking of γ values by a spark at low X/p is of fundamental significance.

Now *Townsend's equation represents a stationary state* and therefore should never be applied to set the condition for a transient phenomenon like the spark. It is thus surprising that the equation should fit the facts. The criterion that $\gamma e^{\alpha\delta}=1$ is, however, amenable to another interpretation as later shown by Holst,[5] by Seeliger[6] and by Holm.[7] The equation represents the condition for a stable self-sustaining discharge. If γ, the fraction of secondary electrons per positive ion, multiplied by the number of positive ions $e^{\alpha\delta}$ created by an electron in crossing the gap is *unity*, then *the discharge continues at its initial value*, i.e., it is *self-sustaining* without outside electrons. If $\gamma e^{\alpha\delta}<1$, then, unless the electron deficit is made up from outside, the discharge goes out. If $\gamma e^{\alpha\delta}>1$, the spark gap accumulates positive ions. The space charges resulting from such accumulations, unless compensated by losses, must lead to an unstable condition which results in a sudden transition to a new mechanism of current maintenance. Thus a photoelectrically sustained current might, when $\gamma e^{\alpha\delta}>1$, undergo, through space charge accumulation at the cathode, a transition to a glow discharge via a discontinuous transient process known as the spark. This interpretation *requires*, however, *a finite time*, of the order of a microsecond, for the building up of a positive ion space charge instability.

2. *Difficulties Encountered by Classical Theory at Higher Pressures*

While this theory sufficed to account for the passage of sparks at relatively low pressures and in short gaps, it is inadequate for sparks exceeding a mm or two above 200 mm pressure. Its shortcomings may be summarized as follows.

(1) The formative time lags of sparks at *atmospheric pressure* have been measured by several methods, which give about 10^{-7} sec. or less, for a one-cm gap at small overvoltages.[8] These time intervals are far below the microseconds required by positive ion movement as postulated above and which have been observed at low values of $p\delta$ by Schade.[30]

(2) At atmospheric pressure the sparking potential has been found to be largely independent of cathode material,[9] although the theory, even though somewhat insensitive to the value of γ at higher pressures, requires a definite dependence of the order of 10 percent on the value of γ.[10] This dependence becomes increasingly important for $p\delta<300$.[9]

(3) In longer sparks, in lightning discharge, and in positive point corona at atmospheric pressure, the character of the cathode is without influence.

(4) Observed appearance of sparks during measurements of α at high values of $p\delta$, with no measurable value of γ, indicates that the theory based on a γ is no longer applicable.[11]

(5) Observations of actual sparks in short time intervals made visible by Kerr cell shutter studies[12] and by cloud track pictures of spark paths after short time intervals,[13] as well as the usual visual observations of sparks, indicate that breakdown at higher pressures occurs along very narrow channels or filaments. This is incompatible with the transient rearrangement of conduction currents in a gas caused by accumulations and movements of positive ions or successive waves of electron ionization when $\gamma e^{\alpha\delta}>1$. This discrepancy is made still more glaring by the zigzag nature of the spark filament and the frequent branching observed in longer sparks.

(6) It is clear that the greater the number of photons incident on the cathode by external irradiation the more rapidly should the space charge accumulation occur, so that formative time lags should decrease as the illumination intensity of the cathode increases. This has been observed at low $p\delta$ by Schade.[30] Observation at atmospheric pressure, however, shows no appreciable change in the *formative* time lag and of the sparking potential with illumination over a considerable range of intensity.[14] When the illumination intensity is increased by a factor of 10^5 beyond that giving the 10^6 electrons/mm^2 sec. generally used, both formative time lag and sparking potential are lowered.[15] In this case the potential is lowered about 10 percent, and the formative time lag appears to be doubled when the intensity of illumination is decreased by a factor of 500. As will later be seen this effect has to do with space charge distortion of the gap by photo-current and cumulative ionization before

the spark takes place. It is not directly concerned with sparking theory.

3. *Nature of Mechanisms Which Must Be Active at Higher Pressures*

Therefore the mechanism of the spark at higher values of $p\delta$ must be essentially different from that at low $p\delta$. A qualitative picture of the process was evolved by Loeb[16] which has very recently been placed on a quantitative basis by Meek.[17] One may begin by considering a plane parallel gap of $\delta=1$ cm length in which the cathode is illuminated by ultraviolet light to such an extent that one electron per microsecond leaves one mm^2 of cathode area. Assume that in air at atmospheric pressure the potential across the plates is 31,600 volts which is the *conventionally* observed sparking potential V_s. The ratio $X/p=41.6$ volts/cm per mm Hg.

a. The Electron Avalanche

Let us then calculate what happens in the field to one of these electrons. It starts across the gap quickly acquiring an average random energy of some $E=\frac{1}{2}mc^2=3.6$ electron volts and a drift velocity v in the field direction of about 1.5 to 2×10^7 cm per second as measured by White[18] and Raether.[19] As it moves it creates new electrons at the rate of α per cm in the field direction so that in a distance x it and its progeny amount to $e^{\alpha x}$ electrons, forming what is called an *electron avalanche*. Therefore, $e^{\alpha x}$ positive ions have been left behind by the electron group, virtually where they were formed in the 10^{-7} sec. of advance for the electrons in the distance $x=\delta$ across the plates. (The mobility of the positive ions is of the order of $10^{-2}-10^{-4}$ that of the electrons.) As the electron avalanche advances, its tip is spreading *laterally* by the random diffusive movement of the electrons. The rate of diffusion of such an avalanche has been experimentally measured by Raether[19] and is found to be about what one would expect from theory based on the velocity v. The average radial distance of diffusion can be calculated from the equation $\bar{r}=(2Dt)^{\frac{1}{2}}$, where $t=x/v$ is the time of advance of the avalanche and D is the coefficient of diffusion which may be estimated from v. From these data it is possible to compute the density of positive ion space charge left behind at any point x. The value of α under these conditions is about 17, making $e^{\alpha\delta}=e^{17}$ or 2.4×10^7. The first ion pair is created at 0.0407 cm from the cathode. At 0.5 cm from the cathode there are 4914 ions, at 0.75 cm there are 3.66×10^5 ions, and within 0.0407 cm from the anode there are 1.2×10^7 ions. Most electrons will be drawn to the anode except for some few that are bound by the positive ions making a sort of a conducting discharge plasma in the avalanche path. The process is schematically shown in Fig. 1 (a) items A, B, C, D and in cloud track pictures taken by Raether[19] of such avalanches as they proceed across the gap with time intervals of 10^{-7} second between pictures as shown in Figs. 1(b) and 1(c).

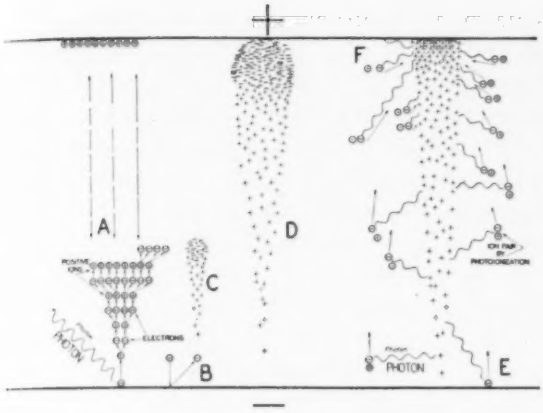
Such a distribution of ions *does not make a conducting filament of charges across the gap* and hence *in itself an avalanche that has crossed does not constitute a breakdown of the gap*. In some 10^{-5} second, the positive ions created could cross the gap. At the cathode, by secondary mechanism, these could lead to the beginning of a Townsend-Holst form of breakdown. However, long before this time interval, the spark has been observed to pass and the discharge is nearly over. Thus one must look further for the mechanism of the spark.

b. Field at Avalanche Tip at Anode

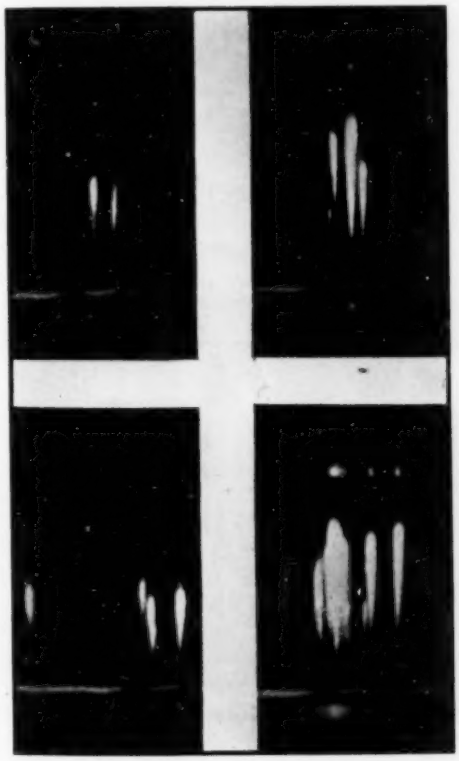
Let us calculate the field due to the positive ions at the anode where they are most densely packed. The ions are in a nearly conical channel with an apex of maximum density at the anode. It is simpler for purposes of calculation to assume that the ions are largely in a sphere of radius r, at the end of the avalanche. From this we can compute the space charge field at the surface from the density of the charge. The field strength X_1 due to this space charge is $X_1=q\epsilon/r^2$, where ϵ is the electronic charge and q is the number of charges in the sphere. Now $q=4\pi r^3N/3$, where N is the ion density. Thus $X_1=4\pi rN\epsilon/3$. In a distance dx at the end of a path x, the number of ions resulting from cumulative ionization is $\alpha e^{\alpha x}dx$ and

$$N=\alpha e^{\alpha x}/\pi r^2. \tag{1}$$

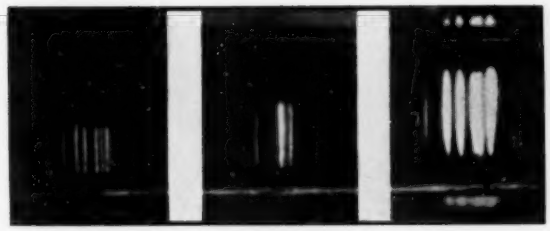
Hence $X_1=4\epsilon\alpha e^{\alpha x}/3r$. Now r is the value of $\bar{r}$ caused by electron diffusion in crossing the gap.



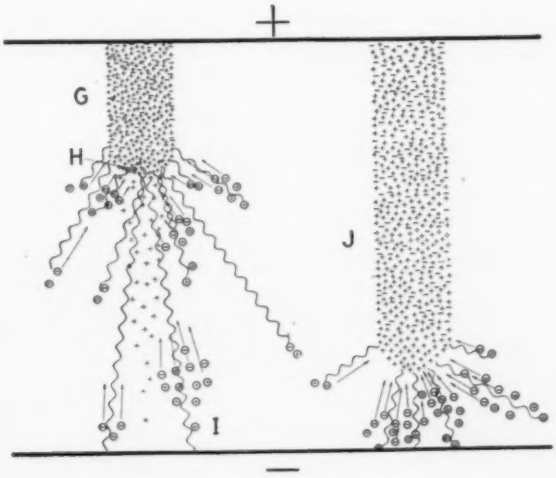
(a) Schematic diagram showing development of a streamer.



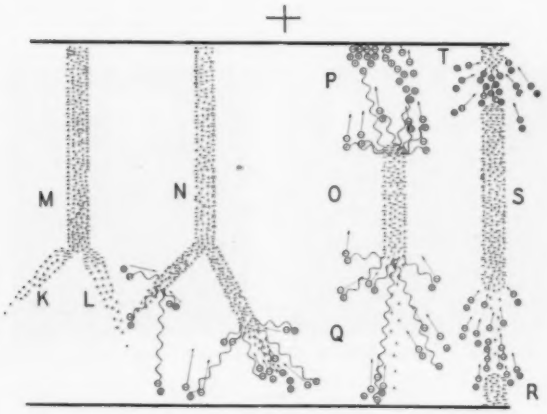
(b) Air at pressure of 270 mm Hg. Field strength-10,500 volts per cm. Difference in duration of applied voltage for (i) and (ii) is 10^{-7} second.



(c) Hydrogen. (i) and (ii) Pressure = 525 mm Hg. Field strength = 11,000 volts per cm. (iii) Pressure = 275 mm Hg. Field strength = 7000 volts per cm. Duration of applied impulse voltage—(i) 1.07×10^{-7} sec. (ii) 1.74×10^{-7} sec. (iii) 2.6×10^{-7} sec.



(d) Schematic diagram showing development of a streamer.



(e) Schematic diagram showing branching and midgap streamers.

FIG. 1. The tracks of electron avalanches as photographed in a cloud chamber. Electrode spacing = 3.6 cm. (The anode is the upper electrode, as in succeeding cloud-chamber photographs.)

Hence $X_1 =$

$$\frac{4\epsilon\alpha e^{\alpha x}}{3(2Dt)^{\frac{1}{2}}} = \frac{4\epsilon\alpha e^{\alpha x}}{3\left(2D\frac{x}{v}\right)^{\frac{1}{2}}} = \frac{4\epsilon\alpha e^{\alpha x}}{3\left(\frac{2D}{k}\cdot\frac{x}{X}\right)^{\frac{1}{2}}} \qquad (2)$$

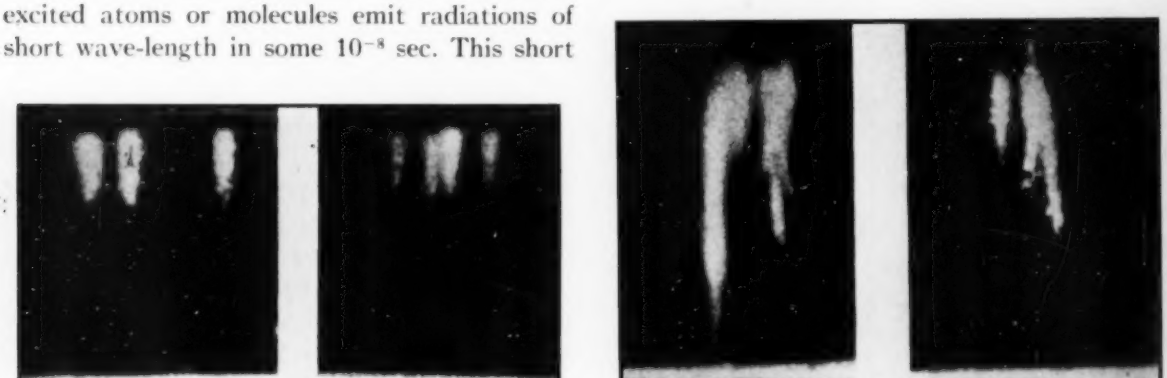
where v is the electron velocity and k is the mobility. For rough calculation r as observed by Raether is $r = 0.013$ cm which makes $X_1 = 6000$ volts/cm or $X_1/X = 0.20$. Thus the field caused by the space charge is 20 percent of the applied field near the cathode. Had an overvoltage of five percent been applied, making $X/p = 43.6$, α would have been 20 and X_1 would have been 140,000. Thus part of the electron swarm would not have crossed the gap completely, for it would have been held back by the heavy space charge some 0.9 of the way across from the cathode.

c. Photoelectric Ionization in Gas

Accompanying the cumulative ionization there are produced by the electrons from four to ten times as many excited atoms and molecules. Some are excited to an energy exceeding the ionizing potential of some of the atoms and molecules present, either by excitation of an inner shell, by ionization and excitation, or in a mixed gas like air by the excitation of molecules of higher ionizing potential, e.g., N_2. These excited atoms or molecules emit radiations of short wave-length in some 10^{-8} sec. This short ultraviolet radiation is *highly* absorbed in the gas and leads to ionization of the gas. The whole gas and the cathode as well are subjected to a shower of photons traveling from the region of dense ionization. Thus nearly instantaneously in the whole gap and from the cathode new photoelectrons are liberated which almost at once begin to ionize cumulatively. Such photons have been observed in corona discharge by Cravath and Dechène,[20] in Geiger counters by Greiner,[21] in parallel gaps with sparks by Paetow,[22] and at the cathode in high pressure positive corona by Kip,[23] as well as in cloud tracks by Raether[23] and Costa.[23]

d. The Positive Streamer Formation

The electrons created at points in the gas and at the cathode at any great radial distance from the avalanche axis will merely create other avalanches. Some of these will be short (from the gas) and others coming from the cathode region will be long and like that of the initial avalanche (Fig. 1(a), items E and F). Being smaller and in any case later in creation than the parent avalanche, such avalanches will be of no interest in breakdown. However, those photoelectrons created near the space charge channel of positive ions left by the initial avalanche, and *especially those near the anode end*, will be in an



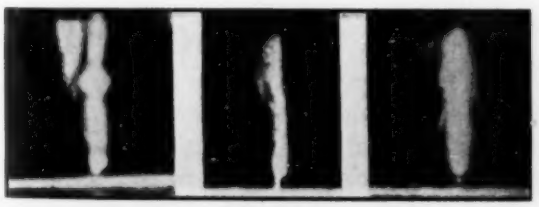
(a) (b)

Fig. 2. The development of electron avalanches and the progress of streamers in a cloud chamber with air at 270 mm Hg pressure. Anode at the top. Electrode spacing = 3.6 cm. Field strength, (a) 10,900 volts per cm, (b) 11,100 volts per cm. These photographs were taken with subnormal expansion ratios. Gorrill (S. Gorrill, Thesis, University of California, 1939) has shown that such expansion produces condensation on uncharged chemical reaction products resulting from intense ionization. Hence, the paths in this, and in Figs. 3 and 9 as well, represent only the dense portions of the avalanches and streamers. In (b), left, note the return streamer which has progressed to near cathode 1; note another streamer with some branching which has not progressed as far. Fig. 2(b), right, shows a well-developed streamer with branching and one avalanche to the left.

enhanced field which exerts a directive action drawing them into itself. If the space charge field, X_1, near the anode is of the order of magnitude of the imposed field X, this action will be very effective.

The electrons from the cumulative ionization of such photoelectron avalanches which are drawn into the positive space charge feed into it making it a conducting plasma which starts at the anode (Fig. 1(a), item *F*). The positive ions they leave behind will extend the space charge towards the cathode. These electrons also create photons which continue this process. The positive space charge thus develops toward the cathode from the anode as a *positive space charge streamer* (Fig. 1(d), items *G* and *J*).

Such streamers have been observed and studied in positive point corona discharge by Trichel,[25] Kip[26] and Loeb.[24,27] They have also been photographed in cloud tracks by Raether,[28] as shown in Figs. 2 and 3. Their velocity of propagation, dependent as it is on photo-ionization in the gas and photon propagation with the velocity of light as well as *short distance motion of electrons in high fields near the space charge*, is extremely rapid. It is undoubtedly more rapid than the velocity of 2×10^7 cm/sec. of the initial electron avalanche.



(a) (b) (c)

FIG. 3. The development of electron avalanches and streamers. Conditions as in Fig. 2 but with higher field strength. In all cases the streamer has returned nearly to the cathode and has produced at the cathode an intense avalanche production moving upward to meet it. In 3(a) note the avalanche head at the anode which has not led to a streamer. Note the branch of the streamer in 3(c).

As the streamer advances towards the cathode it produces a filamentary region of intense space charge distortion along a line parallel to the field, the potential distribution along which is shown in Fig. 4. The conducting streamer of a plasma consisting of electrons and ions extending to the anode thus makes a very steep gradient

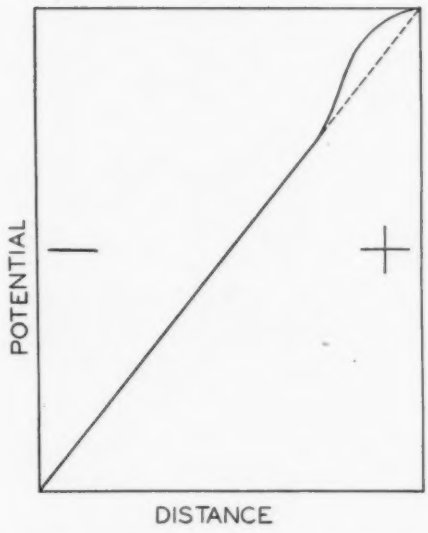


FIG. 4. Schematic representation of the potential distribution in the gap when a streamer is formed near the anode.

at the cathode end of the streamer tip. Here the photoelectron avalanches produced by radiation at the cathode, especially at the intercept of the extended streamer axis at the cathode, begin to produce an intense ionization near the cathode and positive ions created there may also increase the secondary emission (Figs. 1(d) and 1(e), item *R*). Thus, as the space charge streamer approaches the cathode a cathode spot is forming which may become a source of visible light. These are seen in Dunnington's Kerr[12] cell pictures in Fig. 5. When the streamer reaches the cathode there is a *conducting filament bridging the gap*. If then an efficient cathode spot has formed, a heavy return electron current proceeds up the streamer channel at a speed of the order of 10^9–10^{10} cm/sec., and breakdown is completed as a spark.

e. Sparking Potential and Streamer Formation

At just the field strength at which streamer propagation begins, however, the statistical *fluctuations* in the arrival of photoelectrons from the gas at the tip are sufficiently great so that the chance of a continued propagation of the streamer is not very great. Hence, most of the avalanches leaving the cathode cross the gap, start streamers, but fail to cause breakdown.

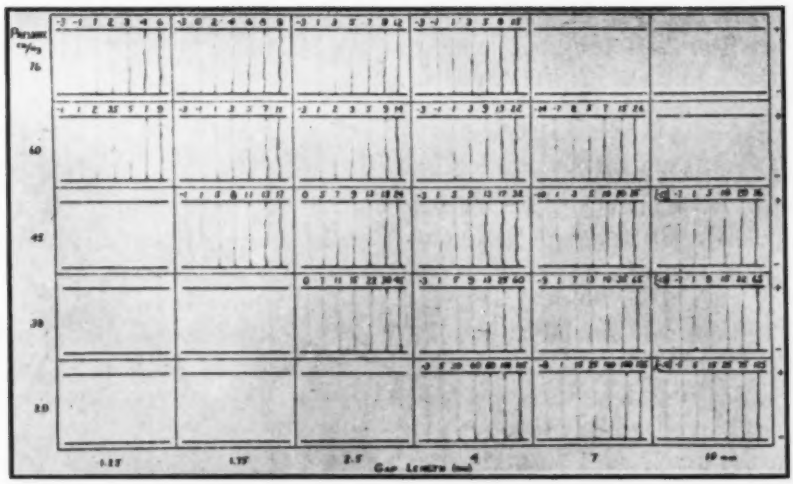


FIG. 5. Dunnington's drawings of the progress of breakdown in air in gaps of various lengths at various pressures as revealed by the Kerr cell shutter. In all cases, the cathode is below, the anode is above. The pressures are indicated on the left, the gap lengths in mm below. Notice that most of these sparks take place at values of $p\delta$ below 200. Thus, most of these sparks are taking place following more or less the Townsend-Holst mechanism. Only at the higher values of $p\delta$ is streamer formation observable. The faint lines before the passage of the spark, which appear to cross the gap, have nothing to do with the spark. According to White they represent Kerr cell background. All gaps were slightly overvolted in order to produce the necessary sparking frequency. This is evidenced by the presence of midgap streamers at higher values of $p\delta$. In all these pictures there is evidence of a cathode streamer which practically vanishes at high $p\delta$. The anode streamers and midgap streamers are most prominent at higher $p\delta$.

Eventually, one electron avalanche will succeed and a spark ensues. This explains the considerable statistical time lags that are observed at the *conventionally* observed sparking potential.[29] Here possibly less than one in 10^6 to 10^8 of the avalanches caused by photoelectrons from the illuminated cathode succeed in causing breakdown.

At this potential the electrons created *at the cathode* have a far greater chance of succeeding in causing breakdown than those liberated *in* the gap. Hence time lags will be greater with γ-ray ionization in the gas than with photoelectrons from the cathode. Actually at the *conventional sparking potential* we are probably already *well above the minimum value at which a very rare streamer can cause a spark*. By speeding up the photoelectric emission to where the very rare avalanches, say one in 10^{10}, which cause breakdown *at the threshold*, occur in the 30 seconds of an observation period at a given potential value, we should expect to find sparks occurring at potentials perhaps some few percent below conventionally observed sparking potential. A further experimental study of the statistical fluctuations of sparks below the *conventional* sparking potential is in progress.

f. Further Characteristics of Streamer Propagation

With the many avalanches feeding into the tip of an advancing streamer, not only may occasional avalanches of considerable strength making a considerable angle with the streamer axis feed in, but often two avalanches of considerable strength may simultaneously feed in from somewhat divergent directions. This leads to the crooked or zigzag path observed in many longer sparks as shown schematically in Fig. 1(e), items *K*, *L* and in Figs. 6[13] and 7.[31] It also leads to the branched or forked sparks so often observed in longer gaps and seen schematically in Fig. 1(e) and in Raether's[28] photographs, Figs. 2 and 3, as well as Figs. 8[32] and 9.[28] The effectiveness of such occurrences will be greater the smaller the field, the longer the gap, and within limits, the lower the pressure. Forking acts to reduce the chance that a given streamer will propagate and cause breakdown.

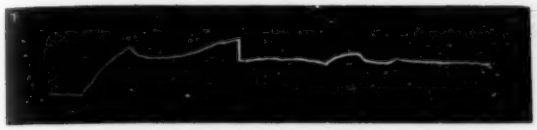


FIG. 6. Photograph taken by Terada and Nakaya of a spark between spheres of 3.0 cm diameter for a gap length of 6.0 cm. This illustrates the zigzag character of the spark channel in long gaps.

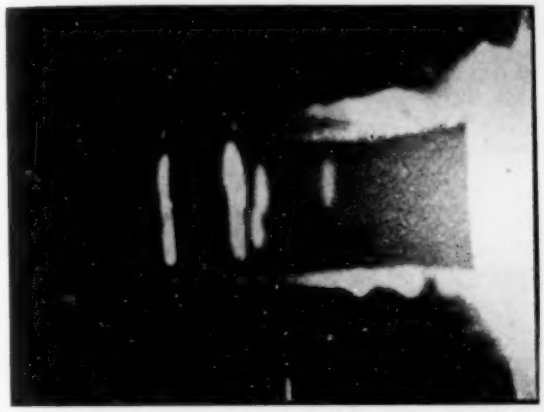


FIG. 7. Cloud track photograph of breakdown of a 2.0-cm plane-parallel gap in N_2 at 225 mm Hg pressure. Applied potential 28,000 volts. Note avalanche at right and two avalanches in center, of which the one to the left exhibits a sharp bend, doubtless caused by a lateral avalanche. The other avalanche in the center is propagating a streamer in the retrograde direction from the anode which might ultimately cause breakdown. The streamer progress has reached the midgap region. (The anode is above, the cathode below.)

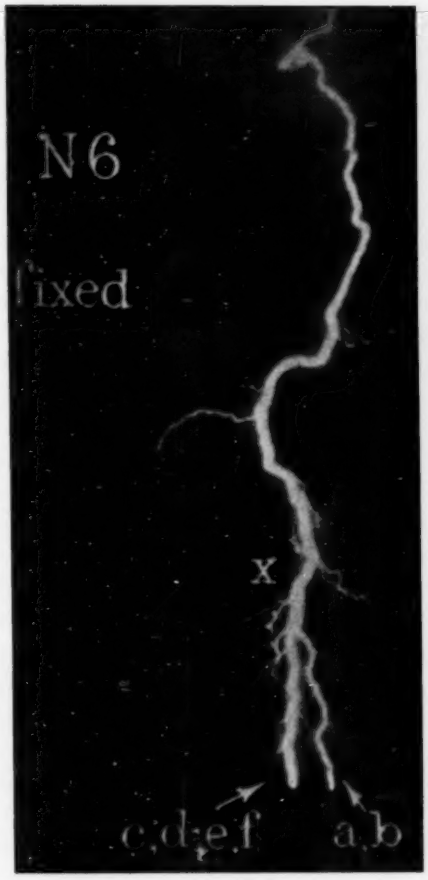


FIG. 8. Photograph of a lightning discharge in which root-branching has occurred.

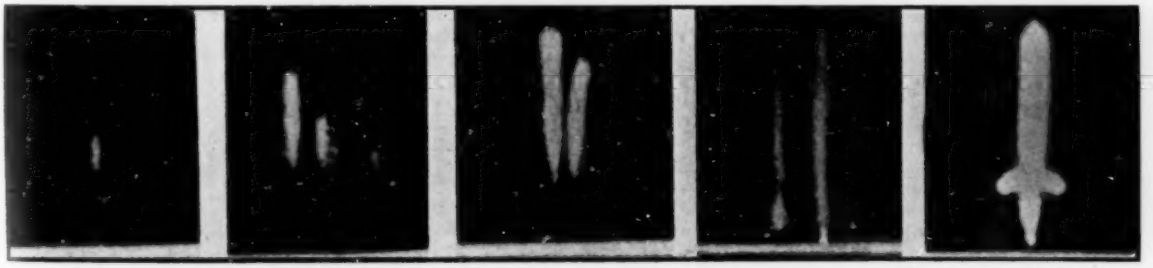


FIG. 9. Raether's cloud track pictures in air with subnormal expansion showing only dense ionization in centers of avalanches and streamers. Photographs (a), (b), (c), (d), and (e) show a gradual increase in the voltage, that in (d) and (e) being sufficient to cause breakdown. The time of exposure to the potential wave is constant and one sees the progress of the avalanche toward the anode. In (d) and (e) the gap has been bridged by the avalanche and a return streamer has followed down the channel to bridge the gap. Note the cathode spots produced as the streamer approaches the cathode. Note also the two well-developed streamer branches in (e). Further note the greater width of the streamer channel over the avalanche channel.

When *overvoltages** are applied, the increase in the value of α will cause the space charge formation needed for streamer formation to occur before the avalanche tip reaches the anode. The streamer will then *start from* some point in the gap in the form of the *midgap streamers* so commonly observed in overvolted gaps in Kerr cell and cloud-chamber studies (Fig. 1(e), items *O* and *S*). Fig. 9 shows the development of streamers from avalanches as fields are increased.[28]

With overvoltage the statistical time lags are very much reduced, or even disappear, since under these conditions almost every avalanche from the cathode has a good chance of initiating the spark. Furthermore, the formative lag will be reduced. Not only are all the processes speeded up in the higher fields, but the midgap streamer action itself produces a shortened time of breakdown. This occurs as follows: The time of electron avalanche advance at $\sim 10^7$ cm/sec. leads to the creation of the space charge for streamer propagation in a shorter distance than the length of the gap. As a result of axial field distortion in *midgap* and photo-ionization by the advancing tip of the negative electron cloud at the anode end of the streamer, photoelectrons will be created in advance of the tip and at the anode. These avalanches cover *short* distances in enhanced fields in reaching the anode. In a short time a positive anode streamer headed for the negative electron cloud of the *midgap* streamer is advancing from the anode, as seen in Fig. 1(e) item *T* and in Fig. 4. The field distortion with midgap streamers is shown in Fig. 10. This action is favored at the anode as the electrons created near there are rapidly drawn in giving a strong positive space charge. Thus essentially the gap is bridged by electron avalanches which traverse only part of the gap in an enhanced field at $\sim 10^8$ cm/sec. and the time consuming electron travel is reduced. This fact has been observed by White,[12] Wilson[33] and others. Pictures of breakdown with midgap streamers show the anode streamer developing as the electron cloud advances to the anode.

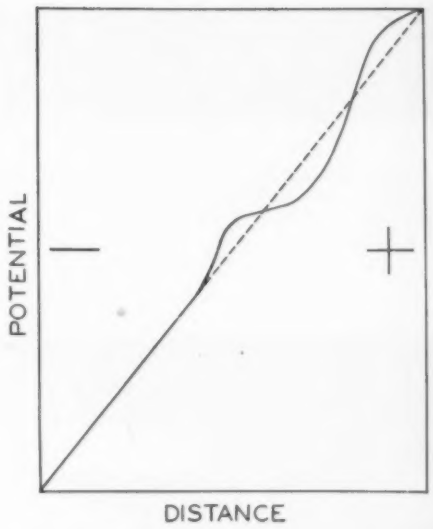


FIG. 10. Schematic representation of the potential distribution in the gap when a midgap streamer and the consequent anode streamer are formed.

* By overvoltage we mean a potential above that *conventionally* observed for the gap, *not* a potential in excess of the minimum or threshold value.

Bibliography

1. J. S. Townsend, Nature **62**, 340 (1900); Phil. Mag. **1**, 198 (1901).
2. L. B. Loeb, R. N. Varney and W. R. Haseltine, Phil. Mag. **29**, 379 (1940).
3. J. J. Thomson, *Conduction of Electricity through Gases* (Cambridge, 3rd edition, 1933), Vol. 2.
4. L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (Wiley and Sons, 1939), p. 416.
5. G. Holst and E. Oosterhuis, Phil. Mag. **46**, 1117 (1923).
6. R. Seeliger, Naturwiss. **16**, 665 (1928); Physik. Zeits. **33**, 273, 313 (1932); R. Seeliger and R. Hirchert, Ann. d. Physik **11**, 817 (1931).
7. R. Holm, Zeits. f. Physik **75**, 171 (1932).
8. P. O. Pedersen, Ann. d. Physik **71**, 371 (1923); J. W. Beams, J. Frank. Inst. **206**, 809 (1928); J. J. Torok, Trans. A. I. E. E. **47**, 177 (1928); **48**, 46 (1930); O. Burawoy, Archiv f. Elektrotech. **16**, 14 (1926); R. Tamm, Archiv f. Elektrotech. **20**, 235 (1928); W. Rogowski, Archiv f. Elektrotech. **20**, 99 (1928); E. O. Lawrence and F. G. Dunnington, Phys. Rev. **35**, 396 (1930); F. G. Dunnington, Phys. Rev. **38**, 1535 (1931); J. C. Street and J. W. Beams, Phys. Rev. **38**, 416 (1931); L. v. Hamos, Ann. d. Physik **7**, 857 (1930); R. Strigel, Wiss. Veröffent aus dem Siemens-Konzern **11**, 52 (1931); **11**, 53 (1932).
9. J. J. Thomson, reference 3, p. 476; L. J. Neuman, Proc. Nat. Acad. Sci. **15**, 259 (1929).

10. L. B. Loeb, Rev. Mod. Phys. **8**, 279 (1936).
11. F. H. Sanders, Phys. Rev. **44**, 1020 (1933); D. Q. Posin, Phys. Rev. **50**, 650 (1936).
12. F. G. Dunnington, Phys. Rev. **38**, 1535 (1931); L. v. Hamos, Ann. d. Physik **7**, 857 (1930); H. J. White, Phys. Rev. **46**, 99 (1934).
13. E. Flegler and H. Raether, Zeits. f. Physik **99**, 635 (1936); **103**, 315 (1936); H. Raether, Zeits. f. Physik **96**, 567 (1935); **112**, 464 (1939).
14. L. B. Loeb, Rev. Mod. Phys. **8**, 280, 285 (1936); *Fundamental Processes of Electrical Discharge in Gases* (Wiley, 1939), pp. 420, 443.
15. H. J. White, Phys. Rev. **48**, 113 (1935); W. Rogowski and A. Wallraff, Zeits. f. Physik **97**, 758 (1935).
16. L. B. Loeb and A. F. Kip, J. App. Phys. **10**, 142 (1939); L. B. Loeb, reference 14, pp. 423, 426–440.
17. J. M. Meek, Phys. Rev. **57**, 722 (1940).
18. H. J. White, Phys. Rev. **46**, 99 (1934).
19. H. Raether, Zeits. f. Physik **107**, 91 (1937).
20. A. M. Cravath, Phys. Rev. **47**, 254(A) (1935); C. Dechêne, J. de phys. et rad. **7**, 533 (1936).
21. E. Greiner, Zeits. f. Physik **81**, 543 (1933).
22. H. Paetow, Zeits. f. Physik **111**, 770 (1939).
23. A. F. Kip, Phys. Rev. **55**, 554 (1939); H. Raether, Zeits. f. Physik **110**, 611 (1938); H. Costa, Zeits. f. Physik **113**, 531 (1939).
24. W. Leigh and L. B. Loeb, Phys. Rev. **51**, 149(A) (1937).
25. G. W. Trichel, Phys. Rev. **55**, 382 (1939).
26. A. F. Kip, Phys. Rev. **54**, 139 (1938); **55**, 549 (1939).
27. L. B. Loeb and A. F. Kip, J. App. Phys. **10**, 142 (1939).
28. H. Raether, Zeits. f. Physik **112**, 464 (1939); F. G. Dunnington, Phys. Rev. **38**, 1535 (1931).
29. A. Tilles, Phys. Rev. **46**, 1015 (1934); M. v. Laue, Ann. d. Physik **76**, 261 (1925); K. Zuber, Ann. d. Physik **76**, 231 (1925).
30. R. Schade, Zeits. f. Physik **104**, 487 (1937).
31. T. Terada and V. Nakaya, Inst. Phys. and Chem. Research, Tokyo, **131**, 1 (1928).
32. B. F. J. Schonland, Proc. Roy. Soc. **A168**, 455 (1938), Fig. 15.
33. R. R. Wilson, Phys. Rev. **50**, 1082 (1936).

Calendar of Meetings

June

17–19 American Society of Heating and Ventilating Engineers, Washington, D. C.
17–21 American Society of Mechanical Engineers, Milwaukee, Wisconsin
18–21 American Association of Physics Teachers, Seattle, Washington
19–21 American Physical Society, Seattle, Washington
20–22 American Physical Society, Pittsburgh, Pennsylvania
24–28 American Society for Testing Materials, Atlantic City, New Jersey
24–28 American Institute of Electrical Engineers, Swampscott, Massachusetts
27–29 Institute of Radio Engineers, Boston, Massachusetts

July

24–26 American Society of Civil Engineers, Denver, Colorado

August

27–30 American Institute of Electrical Engineers, Los Angeles, California

September

9–13 American Chemical Society, Detroit, Michigan

Conference on Applied Nuclear Physics

October 28 – November 2, 1940

A GENERAL Conference on Applied Nuclear Physics, sponsored by the American Institute of Physics in cooperation with the Massachusetts Institute of Technology, will be held during the week of October 28–November 2, 1940, at the Massachusetts Institute of Technology, Cambridge, Massachusetts. The rapidly increasing number of applications of methods and apparatus characteristic of nuclear physics in the fields of biology, radiology, chemistry, geology, and industrial physics has long emphasized the usefulness of a joint conference between physicists and their colleagues in other fields of science.

The purposes of the Conference are to bring together investigators who may be widely separated geographically, and to provide a forum for assembling and correlating present knowledge and difficulties, and for directing attention toward fundamental lines of research which should be the subject of future investigations.

The week's activities will be divided into separate sessions on applications to biology, chemistry, radiology, metallurgy, geology, and to general sessions relating to the production and use of radioactive and stable isotopes, and the protection of workers from radiation. An outline of the general program is given in the following table:

CONFERENCE ON APPLIED NUCLEAR PHYSICS

Digest of Program

Monday A.M., October 28, 1940 (two parallel sessions)

Geology I: "Techniques and Standards in Terrestrial Radioactivity Measurements."
Metallurgy I: "Tracer Studies of Metal Diffusion and Corrosion."

Monday P.M., October 28, 1940 (two parallel sessions)

Geology II: "Geochemical Applications of Radioactivity."
Metallurgy II: "Radiography with Gamma-Rays, X-Rays, and Neutrons."

Tuesday A.M., October 29, 1940 (three parallel sessions)

Geology III: "Radioactive Methods of Geologic Age Determinations."
Chemistry I: "Tracer Techniques in General Chemistry."
Radiology I: "General Aspects of Cancer Therapy."

Tuesday P.M., October 29, 1940 (three parallel sessions)

Geology IV: "Geophysical Applications of Nuclear Physics."
Chemistry II: "Tracer Techniques in Analytical Chemistry."
Radiology II: "Radium and Roentgen Therapy."

Wednesday A.M., October 30, 1940

General I: "Production of Radioactive and Stable Isotopes and of Penetrating Radiations."

Wednesday P.M., October 30, 1940

General II: "Measurement of Radioactive and Stable Isotopes and of Penetrating Radiations."

Thursday A.M., October 31, 1940

General III: "Protection of Workers from Biological Effects of Radiation."

Thursday P.M., October 31, 1940 (three parallel sessions)

Chemistry III: "Synthesis of Organic Substances Containing Tracers."
Radiology III: "Neutron and Artificial Radioactivity Therapy."
Biology I: "Tracer Techniques in Biology."

Friday A.M., November 1, 1940 (two parallel sessions)

Radiology IV: "Dosage Measurements."
Biology II: "Studies of Plant and Animal Metabolism."

Friday P.M., November 1, 1940 (two parallel sessions)

Radiology V: "Radiobiology."
Biology III: "Studies of Plant and Animal Metabolism" (continued).

Saturday A.M., November 2, 1940 (two parallel sessions)

Biology IV: "Studies of Plant and Animal Metabolism" (concluded).
General IV: "Contributed Papers."

Committee in Charge of Program

Robley D. Evans, *Chairman*
Massachusetts Institute of Technology

Elmer Hutchisson, *Secretary*
University of Pittsburgh
Henry A. Barton
American Institute of Physics
Edw. U. Condon
Westinghouse Electric & Manufacturing Company
Lee A. DuBridge
University of Rochester
G. Failla
Memorial Hospital, New York
Clark Goodman
Massachusetts Institute of Technology
Ernest O. Lawrence
University of California
Harold C. Urey
Columbia University

The daily sessions will consist of short invited papers by leading investigators followed by vigorous and searching discussion by the conferees. Ample time will be allowed between and after regular sessions for personal and informal conferences. While the emphasis will be on the program of invited papers and the discussion of these, provision has also been made for a limited number of ten-minute contributed papers. Five one-hour evening sessions will be held, in each of which an outstanding investigator will summarize the status of the several fields which are joined together by the Conference. The evening lectures will be open to the general public.

Anyone who can actively participate in or profit by the Conference is eligible and cordially invited to become a member. Advance registration (no fee) will be required to permit suitable arrangements to be made. Those wishing to attend should register by letter as soon as possible and not later than October 1. Letters and inquiries should be addressed to Professor Robley D. Evans, General Chairman, Conference on Applied Nuclear Physics, Massachusetts Institute of Technology.

Here and There

Cover Photographs

The photographs used on the cover of this issue are by the courtesy of Bacharach Industrial Instrument Company, Brooklyn Thermometer Company, Leeds & Northrup Company, Mason-Neilan Regulator Company, Taylor Instrument Company and Pyrometer Instrument Company.

★

Summer Session, University of Pittsburgh

The Physics Department of the University of Pittsburgh announces the following special graduate courses to be given in the summer session, June 17 to July 26.

Physics of Metals
Introductory Electron Theory of Metals, DR. LEE A. DUBRIDGE, *University of Rochester*
Recent Experiments with Metals, DR. R. P. JOHNSON, *General Electric Company*
Electrical Properties of Metals, DR. W. V. HOUSTON, *California Institute of Technology*
Theories of the Plastic Properties of Metals, DR. FREDERICK SEITZ, *University of Pennsylvania*
X-Ray Diffraction and Structure of Matter, DR. B. E. WARREN, *Massachusetts Institute of Technology*
Experimental Research in X-Rays, DR. S. S. SIDHU, *University of Pittsburgh*
Physics of Glasses
Structure of Glass, DR. B. E. WARREN, *Massachusetts Institute of Technology*
Nuclear Physics
Nuclear Physics, DR. LEE A. DUBRIDGE, *University of Rochester*
Experimental Practice in Nuclear Physics, DR. A. J. ALLEN, *University of Pittsburgh*
Seminar in Nuclear Physics, Conducted by DR. E. U. CONDON, *Westinghouse Research Laboratories*

Schedules of courses and further information regarding these courses may be obtained by writing to E. Hutchisson, Head of the Physics Department, University of Pittsburgh.

★

Guggenheim Fellowships in Physical Sciences

The John Simon Guggenheim Memorial Foundation has recently announced the award of seventy-three fellowships for the academic year 1940–41. Three of these are in the physical sciences:

Dr. David Dennison, Professor of Physics, University of Michigan, is to engage in researches into molecular structure.

Dr. Aristid V. Grosse, chemist, of Bronxville, New York, will investigate catalytic reactions of organic compounds and study the products of neutron bombardment of uranium, protactinium and thorium, at Columbia University.

Dr. Arthur C. Cope, Associate Professor of Chemistry, Bryn Mawr College, plans to make use of the award for studies of the phenomenon of tautomerism.

The Guggenheim Fellowships are awarded to scholars and artists of unusual ability in their respective fields and usually carry a stipend of $2500 a year.

Conference on Differential Analyzer

The differential analyzer, machine for solving ordinary differential equations that are not readily handled by formal methods, will be the subject of a five-day conference to be held at Massachusetts Institute of Technology, Cambridge, Massachusetts, July 8 to 12. The objective of this summer program is to bring to workers outside of M. I. T. an understanding of the scope of the differential analyzer, how it operates in solving a differential equation, what information must be supplied to it, and what techniques can be employed to expedite solutions. It is expected that the new analyzer which has been under construction since 1935 will be in operation at the time of the conference.

There will be no fee for either the lecture or laboratory parts of this conference; however, the size of the group must be limited because of the restricted space near the machines. Persons desiring to attend should write in advance.

★

Cornell Offers Course in Electronics

A course in Theoretical and Experimental Electronics and another on Physical Phenomena from the Point of View of the Wave Theory of Matter, both taught by Professor Lloyd P. Smith, will be offered in the 1940 Summer Session of Cornell University, beginning July 8 and ending August 16. Bulletins regarding the summer program may be obtained from the Director of the Summer Session, Cornell University, Ithaca, New York.

Other courses of intermediate or advanced character which are of special interest to physicists include: Electrical Conduction and Related Phenomena, Optics and Spectroscopy, and Structure of Molecules and Atoms from the Standpoint of Electric and Magnetic Properties. The latter course is being offered by the Department of Chemistry and is to be taught by Professor Peter J. W. Debye.

★

New Editor for *American Weekly*

Robert D. Potter, since 1934 news editor and staff writer in physics and chemistry for *Science Service*, resigned on June 1 to become Science Editor of the *American Weekly*.

★

Case School Appointment

Dr. Robert Sherwood Shankland, Associate Professor of Physics at Case School of Applied Science since April, 1937, and acting Head of the Department of Physics since October, 1939, has been appointed to the position of permanent head of that department, according to a recent announcement. Dr. Shankland is a member of the American Physical Society and of the Acoustical Society of America.

Mathematical Biophysics

The *Bulletin of Mathematical Biophysics* for June, 1940, will contain the following articles:

The Equivalence of the Conduction Theories of Rashevsky and Rushton. ALVIN M. WEINBERG
Further Contributions to the Theory of Cell Polarity and Self Regulation. N. RASHEVSKY
Contributions to the Mathematical Theory of Organic Form. II. Asymmetric Metabolism of Cellular Aggregates. N. RASHEVSKY
A Contribution to the Mathematical Biophysics of Psychophysical Discrimination. III. H. D. LANDAHL
Nerve Conduction Theory: Some Mathematical Consequences of Bernstein's Model. FRANKLIN OFFNER, ALVIN M. WEINBERG AND GALE YOUNG

The editorial and publication offices of the *Bulletin of Mathematical Biophysics* are located at 5822 Drexel Avenue, Chicago, Illinois.

★

Dr. Arthur H. Compton, Professor of Physics at the University of Chicago, has been appointed Dean of the Physical Sciences, a note in *Science* states. On July 1 he will succeed Dr. Henry Gordon Gale, who has served since 1925 as Chairman of the Department and who will become Dean Emeritus of the Physical Sciences.

Professor Hans A. Bethe, of Cornell University, has been appointed visiting Professor of Physics at Columbia University for the next academic year.—*Science*

★

Recent Booklets

"Test tube textiles" is the feature article of the April issue of *The Laboratory*, publication of the Fisher Scientific Company, 711–723 Forbes Street, Pittsburgh, Pennsylvania. The illustrations accompanying the article give varied evidence of the use of synthetic fabrics in the fashions of today.

★

A line of instruments for electrolyte conductivity measurements, in particular the Model RC conductivity bridge and the Model RD Solu-Bridge, is listed and described in a four-page leaflet printed by Industrial Instruments, Inc., 156 Culver Avenue, Jersey City, New Jersey.

Contributors to This Issue

H. T. Wensel

Henry T. Wensel, Chief of the Pyrometry Section of the National Bureau of Standards, received his A.M. and Ph.D. degrees from Johns Hopkins in 1920 and 1923, respectively. Besides extensive work in the measurement of temperature, he has made contributions to the fields of photometry and colorimetry.

A. G. Worthing

A. G. Worthing has been, since 1925, Professor of Physics at the University of Pittsburgh, with charge of the Department from 1925 to 1937. After receiving his Ph.D. degree from the University of Michigan in 1911, Dr. Worthing spent fourteen years with the Physical Laboratory of the National Electric Lamp Association and the Nela Research Laboratory, both of Cleveland.

J. M. Meek

William F. Roeser is a physicist in the Pyrometry Section of the National Bureau of Standards. He has worked there in pyrometry and photometry since 1920. Mr. Roeser received B.S. and M.A. degrees from the George Washington University.

John M. Meek received his B.Eng. and M.Eng. degrees in 1934 and 1936 at Liverpool University, England. From 1934 to 1938 he was with the Metropolitan-Vickers Electrical Company. Mr. Meek came to the University of California in 1938 when he was awarded a Commonwealth Fellowship to the Physics Department.

W. F. Roeser

The following contributors have received mention in earlier issues of the *Journal of Applied Physics:*

W. E. Forsythe, p. 191, Vol. 9, No. 3, 1938.
L. B. Loeb, p. 491, Vol. 8, No. 7, 1937.

Precision

MORE PRECIOUS THAN THE DIAMONDS THAT CREATE IT

IN THE gleaming smoothness of the path behind a diamond cutting tool is visible evidence of the fineness of work the diamond does.

Diamond turning is one method of safeguarding B&L precision. It makes possible machining accuracy that contributes to the precise performance and enduring quality of turned mechanical parts of Bausch & Lomb instruments.

The diamond cuts to closer tolerances, does better work. That is why Bausch & Lomb uses 16,000 carats annually. That is also why, when you want the highest quality and accuracy in an optical instrument, you'll want one bearing the B&L trademark. Bausch & Lomb Optical Co., 670 St. Paul Street, Rochester, New York.

B&L Achromatic
97X Oil Immersion
Objective 1.25 N.A.

BAUSCH & LOMB OPTICAL COMPANY

FOR YOUR EYES, INSIST ON BAUSCH & LOMB EYEWEAR, MADE FROM BAUSCH & LOMB GLASS TO BAUSCH & LOMB HIGH STANDARDS OF PRECISION

APPARATUS DIRECTORY

Temperature-Measuring Equipment

THIS directory is intended to be of service to those who wish to purchase equipment for measuring temperatures. Although an effort has been made to make it cover a wide variety of topics, it does not claim to be absolutely complete. It has been compiled by the editorial staff of the *Journal of Applied Physics* from data supplied by manufacturers of temperature-measuring equipment. Reasonable care has been used to see that the information furnished is accurate, but no responsibility can be assumed by the Journal.

The Directory is divided into the following classifications:

1. Mercury-in-Glass and Similar Thermometers
2. Bimetallic Thermometers
3. Pressure Spring Thermometers
4. Resistance Thermometers
5. Thermoelectric Pyrometers
6. Optical Pyrometers
7. Radiation Pyrometers
8. Automatic Control Equipment
9. Books on Heat and Temperature Measurement
10. Code for Addresses of Manufacturers

1. Mercury-in-Glass and Similar Thermometers

Type	Approximate Range	Smallest Reading	Manufacturers or Distributors
Low Temperature Thermometers			
Pentane-in-glass	−200°C to 20°C	1°	Bro, Cenco, E-A, Fai, Fish, Fu, Grei, Haak, H-B, Sci, Tag
Toluol-in-glass	−100°C to 50°C −150°F to 120°F	1°	Bro, Cenco, E-A, Fai, Fish, Fu, H-B, Sci, Tag, Wel
Intermediate Range Thermometers			
Mercury-in-glass Laboratory, General use (Etched Stem)	(between) −40°C and 360°C −40°F and 680°F	1°, 2°	Bro, Cenco, Dai, E-A, Fai, Flei, Fish, Fu, Gove, Gre, Haak, H-B, Kim, Nu, Pal, Palo, Pec, Phil, Pre, Sci, Tag, Trer, Wek, Wel
Precision laboratory	(between) −40°C and 360°C −40°F and 680°F	1/2°, 1°, 2°	Bro, Cenco, Dai, E-A, Fai, Fish, Fu, Gre, Grei, H-B, Kim, Nu, Pal, Palo, Pre, Sci, Tag, Tay, Trer, Wek, Wel
Industrial	Various	------	Am, Bris, Bro, Cenco, E-A, Fish, Flei, Fu, Grei, H-B, Hill, MMM, Moe, Phil, Pre, Tag, Tes, Trer, Wek
High Temperature Thermometers			
Nitrogen or carbon dioxide above mercury in borosilicate glass	−10°C to 550°C 14°F to 1020°F	1°	Bro, Cenco, Dai, E-A, Fai, Fish, Fu, Gre, Grei, H-B, Kim, Pal, Palo, Sci, Tag, Trer, Wek
Fused silica bulb and stem	100°C to 750°C	5°	Bro

New notes on research in a forward-looking laboratory—

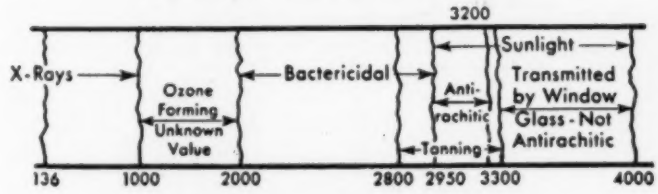
STERILAMP*
developed by Westinghouse

RESEARCH PROVIDES A NEW STEP IN STERILIZATION

Countless developments of modern research are responsible for America's high standards of living and industrial success. Among the more recent discoveries is the STERILAMP, developed by two scientists in the Westinghouse, Bloomfield, Laboratory.

Bacteriologists had already determined the most effective bactericidal radiation and it remained for these two scientists to produce the bactericidal radiations without the useless and often deleterious radiations which usually accompanied them. Such a generator was developed, high in efficiency for producing the desired wave lengths, low in power consumption, low in producing non-bactericidal radiation, and, furthermore, controlling the radiation responsible for ozone generation. The diagram shows the relatively small portion of the ultraviolet spectrum known to be bactericidal.

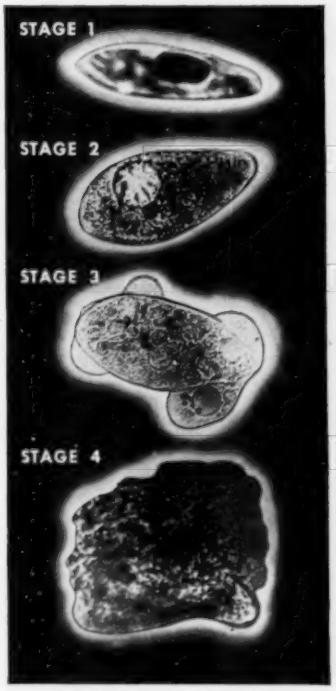
ULTRAVIOLET PORTION OF SPECTRUM



ÅNGSTRÖM UNITS

The STERILAMP, the trade-mark which is aptly applied, produces practically 80% of its radiation near the peak of the bactericidal region in the ultraviolet spectrum.

This product of modern research has already been established in the food preservation field and evidence points to thousands of dollars already saved. Its use has been expanded to air sterilization in hospital operating rooms and general air conditioning systems, sanitization of drinking glasses in restaurants, and countless other applications.



This remarkable series of pictures shows how rays from the STERILAMP kill micro-organisms. Stage 1, normal paramecium; Stage 2, after thirty seconds of irradiation; Stage 3, cell wall continues to weaken; Stage 4, finally dies of internal explosion which bursts its outer skin.

FOR COMPLETE INFORMATION ON THE STERILAMP WRITE TO WESTINGHOUSE RESEARCH LABORATORIES, BLOOMFIELD, NEW JERSEY

*Trade-mark Reg. U. S. Pat. Office

1. Mercury-in-Glass and Similar Thermometers (continued)

Short Scale and Special Purpose Thermometers

Calorimetric	16°C to 40°C 60°F to 105°F	1/10, 1/20, 1/50, 1/100°	Bro, Cenco, Dai, E-A, Fish, Fu, Gre, Grei, H-B, Kim, Parr, Pre, Sci, Trer, Wek
Beckmann	6°	1/100°	Bro, Cenco, Dai, E-A, Fish, Fu, Grei, H-B, Nu, Palo, Sci, Wel
Special purpose, ASTM standards, etc.	Various	– – –	Am, Bro, Cenco, Co, Dai, Def, E-A, Eis, Fai, Fee, Fish, Flei, Fri, Fu, Gove, Gre, Grei, Haak, H-B, Kim, Mar, Pal, Palo, Phil, Pre, Sci, Tag, Tay, Tes, Trer, Wek

2. Bimetallic Thermometers

Type	Ranges Between	Smallest Reading	Manufacturers or Distributors
Dial indicating	−18°C and 260°C 0°F and 500°F		Cenco, Co, Dill, Fee, Fu, John, Roc, Stan, Wes
Recording	−29°C and 43°C −20°F and 110°F	1°, 2°	Cenco, Fri, Fu, Mar, Prac, Ryan, Stan

3. Pressure Spring Thermometers

Type	Ranges Between	General Characteristics	Manufacturers or Distributors
Indicating			
Vapor pressure	−35°C and 320°C −30°F and 600°F	Thermal system is filled with volatile liquid and its vapor. Bulb is small and response is very quick. Sensitivity is high and instrument is especially useful for narrow temperature ranges. Normally no compensation needed. Scale is not linear.	Bris, Brown, Fox, MMM, Mar, M-N, Moe, Part, Po, Tag, Trer, USG, Whe
Gas filled	−100°C and 650°C −150°F and 1200°F	The thermal system is filled with inert gas under pressure. Useful for wide temperature range. Scale may be uniform. Bulb is large and slow in responding.	Bris, Brown, Def, Fox, MMM, Mar, M-N, Moe, Tag, Trer, Whe
Liquid expansion	−100°C and 260°C −150°F and 500°F	The thermal system is filled with an expansible liquid. Compensation ordinarily needed. Fairly rapid in response. Scale may be uniform. Bulb is small. Range not as great as gas filled.	Bris, Brown, Fox, MMM, M-N, Moe, Moto, Pal, Tag, Trer, Whe
Recording			
Vapor pressure	−35°C and 320°C −30°F and 600°F	See above	Bris, Brown, Fox, MMM, Mar, M-N, Moe, Po, Tag, Trer, Whe
Gas filled	−100°C and 650°C −150°F and 1200°F	See above	Bris, Brown, Def, Fox, MMM, Mar, M-N, Moe, Repu, Tag, Trer, Whe
Liquid expansion	−100°C and 260°C −150°F and 500°F	See above	Bris, Brown, Fox, MMM, M-N, Moe, Moto, Pal, Tag, Trer, Whe

4. Resistance Thermometers

Unit consists of resistor (usually in bulb), leads, bridge and indicator or recorder.

Material	Approximate Range		Manufacturers or Distributors
Nickel or special wire in metal tube.	−200°C to 200°C −330°F to 400°F	Made in both industrial and high precision types.	Bris, Brown, Eng, Ill, L-N, Tag, T-A
Platinum in Pyrex or metal tube	−200°C to 500°C −330°F to 930°F		Bak, L-N, Tag, T-A
C.P. platinum in quartz tube	−200°C to 900°C −330°F to 1600°F		Bak, Eng
Bridges for resistance measurements			Cenco, L-N, Rub, Wes, Whe

Photographic Plates for Scientific Purposes

MORE THAN FIFTY special kinds of plates for scientific work are made in Kodak Research Laboratories. They permit photography in spectral regions ranging from the short ultraviolet to the infrared at 12,000 Å., and include five degrees of speed and contrast.

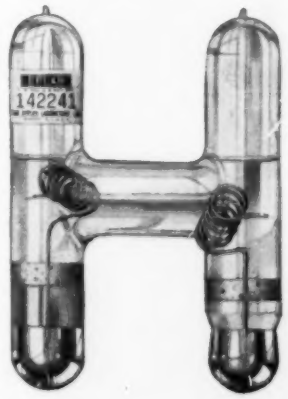
The characteristics of these plates are described in the publication, *Photographic Plates for use in Spectroscopy and Astronomy*, a copy of which will be sent free on request.

Be sure to visit the Kodak Building at the New York World's Fair

EASTMAN KODAK COMPANY

Research Laboratories **ROCHESTER, N. Y.**

EPPLEY STANDARD CELLS



For more than 20 years the leading American manufacturers of industrial temperature control apparatus have used Eppley Standard Cells in their recorders, pyrometers and other instruments utilizing the potentiometric system of measurement.

We feel that this almost universal adoption of the Eppley Standard Cell is the result of high standards of quality and reliability, achieved and maintained through years of painstaking research, which still continues in an endeavor to render American industry a service of ever-increasing value.

When you purchase an instrument containing an Eppley Standard Cell you are obtaining maximum standard cell efficiency and reliability. The best testimonial to this fact is 20 years acceptance by American manufacturers.

EPLAB

THE EPPLEY LABORATORY, INC.

SCIENTIFIC INSTRUMENTS

NEWPORT, R.I.

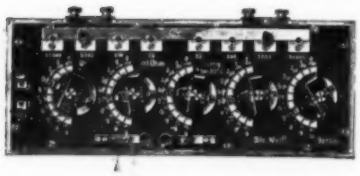
U. S. A.

5. Thermoelectric Pyrometers

Unit consists of thermocouple element, protection tube, and indicating or recording meter.

Material	Measures temperatures up to	Manufacturers or Distributors
Base Metal		
Iron constantan	870°C 1600°F	Bris, Brown, E-A, Eng, Gor, Ill, L-N, Raws, Rich, Tag, Tam, T-A, Whe
Nickel-chrome nickel-manganese	1100°C 2000°F	T-A
Copper constantan	400°C– 815°C 750°F–1500°F	Eng, Gor, Rich, Tag, T-A
Nickel-chrome constantan	900°C 1650°F	T-A
Nickel-chromium nickel-aluminum	1000°C 1830°F	T-A
Chromel-Alumel	1350°C 2450°F	Bris, Brown, Cenco, E-A, Eng, GE, Gor, Hos, Ill, L-N, Marsh, Rich, Tag, Whe
Chromel-constantan		Gor, Ill, Whe
Chromel-copel	550°C 1020°F	Hos
Rare Metal		
Thermocouple Material	Measures temperatures up to	Manufacturers or Distributors
Platinum—10% platinum-rhodium Platinum—13% platinum-rhodium	1540°C 2800°F	Bak, Bis, Bris, Brown, Cenco, E-A, Eng, Ill, L-N, Rich, Tag, T-A
Platinum gold-paladium	1000°C 1830°F	Bak

Potentiometers and Other Meters



Wolff precision potentiometer for measurements of resistance and potential in research, engineering and standardizing laboratories. This instrument is of highest precision and useful as a primary standard. Bid

Potentiometer and millivoltmeter types of recording and indicating potentiometers. Colored numeral records may be made. Cold junction temperature is equalized. Brown

Wide strip recorder with enclosed mechanism, operating on the potentiometer principle. Mechanical backlash is taken up. Recording is by pen and ink. Cold junction compensator is built in. Bris

Ferrotemp is a portable instrument for the determination of molten gray or white iron temperatures while the metal is still in the ladle. It consists of a platinum, platinum-rhodium thermocouple; gas-tight refractory tube and a carbon base protector shield; and a large meter reading up to 3100°F. Die

Switchboard indicator made with scales for use with various kinds of thermocouples. A dummy pointer is provided to indicate a temperature at which a furnace should be held. Eng

Temperature indicator available for panel mounting or portable service. May be used in connection with melting pots, ovens, heated liquids, etc. Calibrated for use with Chromel-Alumel thermocouples and made with ranges up to 1500°F. GE

A 20-point transfer switch is available so that one potentiometer may be used with 20 thermocouples. GE

Thermocouple potentiometer mounted in a box containing a 500-microampere galvanometer. Scale is marked in millivolts and also temperatures reading to 140°C. For use with GE special-alloy thermocouples. Cold junction compensator is provided. Error is usually less than 1 percent of full-scale value. GE

NEW McGRAW-HILL BOOKS

THE MODERN THEORY OF SOLIDS

By FREDERICK SEITZ, University of Pennsylvania. *International Series in Physics.*
In press—ready in June

In this distinctive new book the author presents a survey of the theory of the properties of all types of crystalline solids. The book is unique in that it covers the theory of all types of solids from a common viewpoint. Besides dealing with the theory of metals, the author treats the properties of salts and other insulators as well, showing the factors which account for differences and similarities of all these materials.

APPLIED X-RAYS. *New third edition*

By GEORGE L. CLARK, University of Illinois. *International Series in Physics.*
In press—ready in June

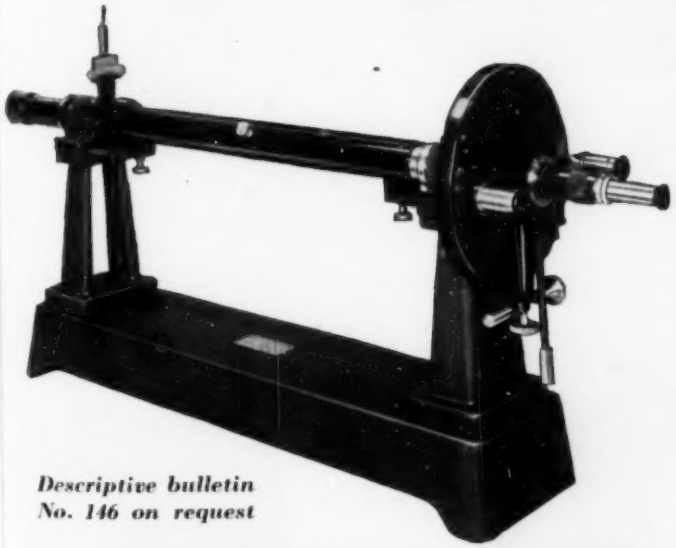
The author of this well-known book, besides bringing the material up to date, has expanded the text considerably to include the remarkable developments of the past eight years. The chapter on interpretation of X-ray diffraction patterns is entirely new, and new chapters have been added on the measurement of intensity, photochemistry, the biological effects of X-rays, etc.

Send for copies on approval

McGRAW-HILL BOOK COMPANY, INC.

330 West 42nd Street New York, N. Y.

LIPPICH TRIPLE FIELD POLARIMETER



Descriptive bulletin No. 146 on request

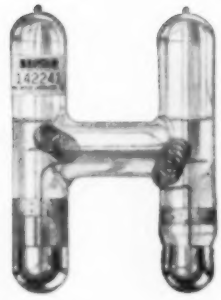
The *GAERTNER* polarimeter is designed to permit repeated readings to 0.01 degree. This **accuracy** is assured by the amply large precision circle and the high grade quality of the optical parts. Tubes up to 400 mm in length can be accommodated.

The instrument is designed for greatest permanence and the rugged construction gives long and trustworthy service.

THE GAERTNER SCIENTIFIC CORPORATION

1212 Wrightwood Ave. Chicago, Illinois

Potentiometers and Other Meters (continued)

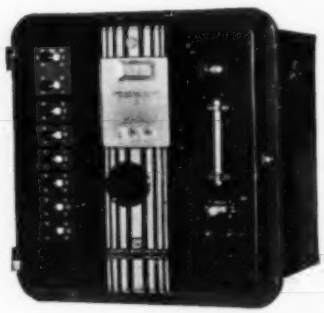


Standard cells for use in pyrometer recorders or other temperature control apparatus utilizing potentiometric systems. Epp

Hoskins Type A.H. portable pyrometer of high resistance voltmeter type. Uses Chromel-Alumel couple. Also made for wall mounting and with automatic temperature controller. Hos

Portable potentiometer for thermocouple measurements in industrial plants. Low range, 0 to 16 millivolts, and high range, 16 to 64 millivolts. May be read to about 0.05 millivolt. Galvanometer, battery, and standard cell included in case. L-N

Model R Micromax recorder; indicates on extra-bold circular scale; records in ink on a 24-hour circular chart. Instrument may be used either as potentiometer or bridge for thermocouples or resistance thermometers. Can be equipped to operate automatic control systems. L-N

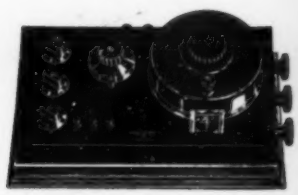


Panel indicator for near or distant thermocouples. Operator switches desired detector into the circuit and rotates knob until pointer comes to zero, thus obtaining the temperature reading. Both single and double range instruments are provided. L-N

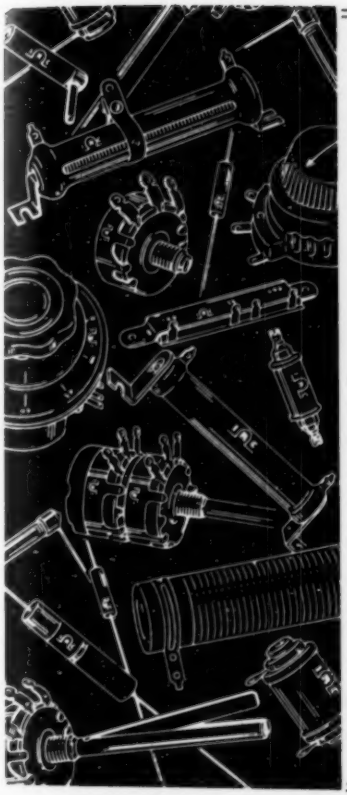
Portable precision potentiometer for checking thermocouples in plant and laboratory. Two ranges, from 0 to 80 and from 0 to 16 millivolts. Smallest scale division is 0.01 millivolt. Lamp and galvanometer scale are built into the instrument. L-N

Model S Micromax recorder; temperatures are recorded in ink on a moving chart. Temperatures from 16 points in 6 contrasting colors may be recorded at once. Instrument may be used either as a potentiometer or as bridge. It is available in many different ranges. L-N

Rotary type switches suitable for connecting a number of thermocouples to an indicator. Switches are made for twelve, ten, or five thermocouples. L-N



Type K-2 precision potentiometer with triple range. Low range is especially useful for checking industrial pyrometers. Maximum readings on each range are 1.61, 0.161, and 0.0161 volts. Smallest reading is 0.1 microvolt. L-N



RESISTANCE ENGINEERING DATA BULLETINS

These IRC Resistance Engineering Data Bulletins contain the results of many years of specialized experience in the production of more resistance types for more applications than any other manufacturer in the world. They have been classified and prepared to bring exact needed engineering information to assure selection of the *right* resistor for *any* job. Please ask for them by number.

1. Metallized and Wire Wound Volume Controls and Potentiometers up to 2 watts and 20 meg. resistance.

2. Metallized Type Resistors: Insulated 1/2, 1 and 2 watts; high frequency; high range; high frequency power resistors; high voltage power resistors.

3. Insulated Wire Wound Resistors: Type BW from 1/2 to 1 and 2 watts; Type MW 5 to 20 watts.

4. Power and Precision Wire Wound Resistors: Power types from 10 to 200 watts, fixed and adjustable types, in wide variety of shapes, mountings, etc. Inductive and non-inductive. 14 Precision types to as close as 1/10 of 1% accuracy.

5. Attenuators: Unique new IRC molded motor commutator type 20-step attenuator; also, conventional type 30-step units. Ladder, Potentiometer or Bridge T.

6. Power Rheostats: Quick heat-dissipating all-metal (aluminum) 25 and 50 watt types.

IRC

INTERNATIONAL RESISTANCE CO.

419 N. BROAD ST., PHILADELPHIA, PA.

THE SOCIETY OF EXPLORATION GEOPHYSICISTS

Articles Published in *GEOPHYSICS*, Volume IV, Number 3 (July, 1939)

The Relation of Geophysics to Geology — *F. M. Kannenstine*

On the Strategy and Tactics of Exploration for Petroleum, III — *E. E. Rosaire*

A Problem in Seismic Depth Calculation — *Roland F. Beers*

Determination of Density for Reduction of Gravimeter Observations — *L. L. Nettleton*

Terrain Corrections for Gravimeter Stations — *Sigmund Hammer*

Concentrations of Hydrocarbons in the Earth — *Eugene McDermott*

On Geochemical Prospecting — *Leo Horvitz*

The subscription rate is $6.00 yearly in the United States, $6.50 elsewhere. Back numbers are obtainable at $3.00 in the United States, $3.20 elsewhere. The following back numbers are available:

1935—Vol. VI, No. 1, *Journal of the Society of Petroleum Geophysicists* (supply limited)

1936—Vol. I, Nos. 2 and 3, *Geophysics* (No. 1 out of print)

1937—Vol. II, Nos. 1, 2, 3 and 4, *Geophysics*

1938—Vol. III, Nos. 1, 2, 3 and 4, *Geophysics*

Orders should be addressed to

THE SOCIETY OF EXPLORATION GEOPHYSICISTS

P. O. Box 777, Austin, Texas

Linde

RARE GASES AND MIXTURES

NEON
ARGON
HELIUM
KRYPTON
XENON
MIXTURES

. . . highest purity
. . . for scientific purposes

Linde rare gases are of consistently high purity. They are used in the study of electrical discharges, in rectifying and stroboscopic devices, and in inert atmospheres where heat conduction must be reduced.

Linde rare gases are shipped in spherical glass bulbs, designed to facilitate removal without contamination. Special mixtures for experimental purposes can be supplied upon request.

The Linde Air Products Company

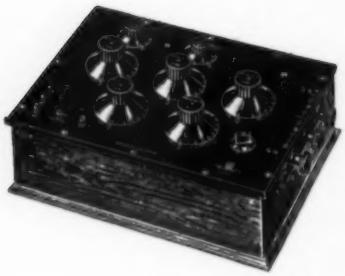
Unit of Union Carbide and Carbon Corporation

30 East 42nd Street UCC New York, N. Y.

Offices in Principal Cities

The word "Linde" is a trade-mark.

Potentiometers and Other Meters (continued)



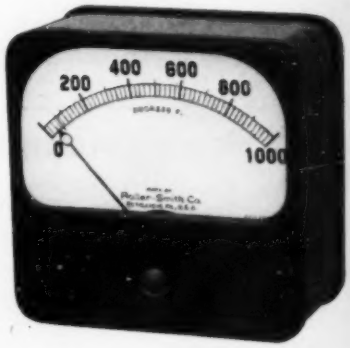
Wenner thermocouple potentiometer for measurement of low voltages. Two ranges: 0 to 0.11111 volt in steps of 1 microvolt; and 0 to 0.011111 volt in steps of 0.1 microvolt. Enclosed switches. L-N

Portable precision potentiometer which may be used for thermocouple measurements. Ranges from 0 to 10.1, to 0 to 161 millivolts. Smallest marked division, 0.005 millivolt. This instrument is equipped with self-contained standard cell, battery and galvanometer, but may be connected with external galvanometer. Rub

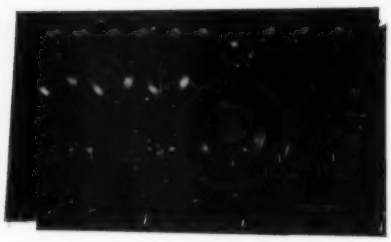
Portable slidewire potentiometer for thermocouple use and calibrated to read directly in temperatures. Instruments have self-contained standard cell, battery and galvanometer. Rub

Potentiometers and associated equipment. *Celectray* potentiometers and Wheatstone bridges for indicating, recording and/or controlling single or multiple point, calibrated for use with any type of thermocouple, resistance thermometer or d.c. voltage above 1-millivolt span of potentiometers and 25°C of Wheatstone bridges for resistance thermometers, photoelectric controllers for a.c. bridges. Special high speed single point recorders and self-balancing indicators. Controllers fitted for all modes of control including automatic reset. Tag

Indicating pyrometer for built-in applications for use with iron-constantan or Chromel-Alumel couples. Designed in ranges up to 2000°F. R-S



Indicating pyrometer for built-in applications for use with platinum-platinum rhodium couples. Range 0–2500°F with a smallest reading of 30°. R-S



High precision potentiometer, type B; calibrated to read 0 to 161 millivolts; 0 to 160 millivolts; and 0 to 1.6 volts. Smallest marked division is 0.0005 millivolt. This is a general purpose laboratory potentiometer. Rub

Photoelectric potentiometer measures small voltages or currents. High sensitivity vacuum-tube amplifier is used so that output can be applied to rugged instruments. Recorders or relays can be operated in remote positions. Instrument operates at very high speed. Wes

White single potentiometer for precision temperature measurements in calorimetry. Range, 0 to 0.01 volt in steps of 1 microvolt, or 0 to 0.1 volt in steps of 10 microvolts. Can be supplied as a "double" potentiometer where it is necessary to measure practically simultaneously two temperatures which are appreciably different and both changing rather rapidly but at about the same rate. L-N

PORTABLE POTENTIOMETERS

Rubicon portable potentiometers are available in a variety of single and double range models suitable for thermocouple, pH and instrument calibration work. Guaranteed accuracy to .1%.

These sturdy, self-contained instruments are built to give years of satisfactory service under all conditions encountered in the laboratory, shop or field. They are outstanding values in their class.

Ask for Bulletin 270.

RUBICON COMPANY

Electrical Instrument Makers

29 North Sixth Street Philadelphia, Pa.

Surplus Stock of

OPTICAL GLASS

at special prices

Changes in design of instruments have left us with a surplus stock of certain melts of optical glass. Quantities up to 500 lbs. are available of some kinds.

Send for catalog giving complete specifications, quantities and low prices.

Spencer Lens Company

Buffalo New York

AMINCO

ELECTRIC HEATERS

LoLag & Controls

AVAILABLE in the following improved types for the safe, economical and efficient utilization and application of electric heat.

IMMERSION HEATERS . . . . flexible type in lengths up to 13 ft. that can be bent to any shape for symmetrical distribution of heat; also screw-in type with standard pipe threads for screwing into tanks, etc. Both types are available with sheaths of copper, steel, stainless steel or monel metal. They respond instantly to regulator action . . . ideal for precise constant temperature work.

OVEN AND SPACE HEATERS . . . open coil type for grouping in any arrangement.

ROOM HEATERS . . . convection type for heating otherwise hard-to-heat isolated places such as offices, rooms, etc.

NEW CATALOG SI-2075
Gives Full Details

AMERICAN INSTRUMENT CO.
8010 GEORGIA AVENUE · SILVER SPRING, MARYLAND

EXTREMES

A 4½" bellows capable of 1¾" movement; and a 1⅝" bellows capable of 350 lbs. pressure per square inch.

HYDRON

Metallic Bellows

HYDRON Metallic Bellows are used as control elements in temperature-and-pressure-control devices, and for liquid or gas seals of compressors and pumps. We are specialists in the design and production of complete thermostatic and pressure units for temperature and pressure controls. We are, therefore, prepared to extend the fullest co-operation to engineering departments of control manufacturers in the solution of design and engineering problems.

Write for 44-page Engineers' Data Book.

CLIFFORD MANUFACTURING CO.

BOSTON CHICAGO DETROIT LOS ANGELES

PRODUCERS OF BELLOWS EXCLUSIVELY
SERVING AUTOMATIC CONTROL MANUFACTURERS

Potentiometers and Other Meters (continued)

Microvolt potentiometer for the precise measurement of thermocouple voltages. Four ranges: −0.10 to 100.10; −1.00 to 1001.00; −10.0 to 10010.0; and −100. to 100100. microvolts. Smallest marked division is 0.01 microvolt. Resistances are manganin and instruments are designed particularly to eliminate parasitic thermal e.m.f.'s. Rub

Type JR pyrometer designed particularly for industrial applications. Two standard ranges; 80°F to 1200°F, and 80°F to 2400°F. A selector switch is provided in several sizes up to 28 thermocouple contacts. Instrument may be equipped with an internal automatic cold junction compensator. T-A

Indicating pyrometer of direct-reading millivoltmeter type. Switch is provided with any number of contacts up to 32. T-A

Rawson ultra-sensitive semi-suspended millivoltmeters may be used for thermocouples. Smallest division, one microvolt. Standard single or double pivot portable meters also available reading to 0.01 millivolt. Raws

Accessories

Protection tubes, insulators and terminal heads, connectors, etc. Bris, Brown, E-A, Eitz, Eng, Gor, Hos, L-N, Rich, Tag, T-A, Whe

6. Optical Pyrometers

Bacharach optical pyrometer; ranges between 1150°F and 4800°F. Adjustable, double color filters incorporated into instrument. Bac

Pyro-optical pyrometer; supplied in ranges between 1400°F and 3700°F (to 5500°F or corresponding centigrade scales on special request). Furnished complete with master lamp, two service lamps, leather-covered steel carrying case and straps for instrument and case. For industrial use. Pyro Bueh

Brown Optimatic; an automatic self-balancing optical pyrometer. Makes use of a photo-cell and may be used for high speed recording or indicating of temperatures of moving objects. Upper temperature limit, 3000°F. Brown

Pyro micro-optical pyrometer; for use in measuring the temperature of small objects, such as incandescent lamp filaments. Scale ranges between 600°C and 4000°C (or Fahrenheit equivalents). Pyro

FINE WIRES

TAYLOR PROCESS

THE TAYLOR PROCESS is a method for making wires from substances which lack ductility. The elements or alloys, because the drawing is done in glass or quartz, are in a very pure state. Lengths of more than a few feet cannot be obtained. The wires may be had with or without the glass insulation. We make Taylor Process wire of Pt, Rh, Au, Ag, Cu, Fe, Zn, Cd, Pb, Sb, Bi, Sn, Se, Te, Tl, Ga, and In, Constantan, Bi-Sn, Cd-Sb (used where large E.M.F. is desired) and many other alloys. Our wires are packed in containers holding one foot and, with few exceptions, the sizes are from one *mm* to one micron. We manufacture, too, fine wire by the Wollaston Method, by extrusion and by bare drawing.

WE ARE SPECIALISTS IN PLATINUM AND CAN SUPPLY IT IN WHATEVER FORM YOU REQUIRE

BAKER & CO., INC.

113 Astor Street, Newark, New Jersey

SHALLCROSS

HIGH ACCURACY

Resistance Standards

Having wide application in practically all fields of electrical measurements, these instruments are accurately calibrated to provide high resistances totaling 1 megohm. Have two 100,000 and four 200,000 ohm taps. Resistance coils are non-inductively wound on non-hygroscopic ceramic spools, using Manganin wire. Carefully aged to insure permanence of calibration. Limit of error — .05%.

We also manufacture similar instruments for any combination of resistances desired.

Write for Bulletin BA—810

SHALLCROSS MFG. COMPANY

INSTRUMENTS - RESISTORS - SWITCHES

COLLINGDALE, PA.

DO YOU TEACH PHYSICS TO STUDENTS OF ENGINEERING?

If so, you will want to examine

Hammond's PHYSICS

A Text for Science and Engineering Students

Contains 760 pages, 6 by 9 inches, 829 illustrations and 689 problems.

The text may be obtained in single volumes, $4.75, or in two volumes, $2.60 each.

This text is the result of many successful years of teaching in this field, and it has been used in the author's classes since 1932.

The author's students use their texts as reference books after their physics course is completed.

The treatment of the topics is direct, concise, yet complete. Says one teacher, "The familiar title of the book gives no warning of the very unusual presentation of the subject matter but as soon as one starts reading it, it does not take him long to find it out."

Another says, "The book is accurate, and the parts are well balanced."

Copies for examination may be obtained upon request and a reasonable time will be allowed for examination.

MOUNTAIN STATES PUBLISHING COMPANY

BOX 912

LARAMIE, WYOMING

"POINTOLITE" *Lamps*

BRILLIANT—CONCENTRATED—STEADY—WHITE

When an evenly distributed field of illumination is needed . . . or a light source of constant intensity . . . or one that will remain in a fixed position . . . use Pointolite Lamps. Let us tell you more about these highly concentrated sources of white light and their various applications.

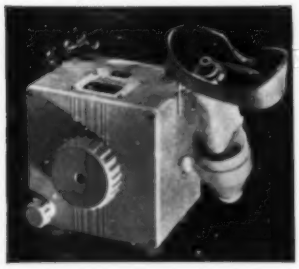
Bulletin 1630-R lists sizes from 30 to 1000 c.p. for direct current, and 150 c.p. for alternating current, as well as auxiliary control devices. . . . Write for a copy.

JAMES G. BIDDLE CO.

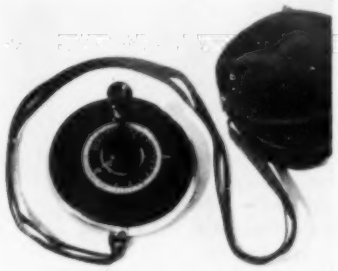
ELECTRICAL INSTRUMENTS

1211-13 ARCH STREET PHILADELPHIA, PA.

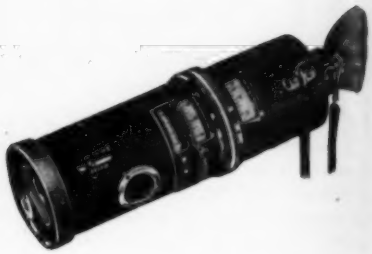
Optical Pyrometers (continued)



L and N optical pyrometer—potentiometer type; supplied in ranges between 1400°F and 5200°F. Direct-reading; potentiometer calibrated in degrees. Lightweight alloy case. L-N

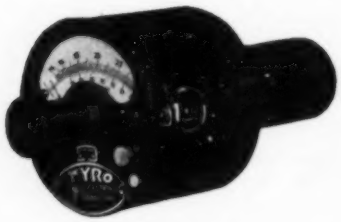


Eastman color temperature meter designed to check the quality of illumination for photographic purposes. Essentially it determines color temperature of incandescent filament. EKC

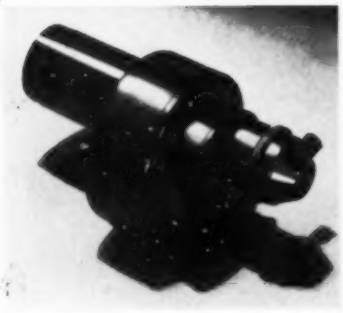


Pyro bi-optical pyrometer; for technical and scientific research purposes. Scale range, 1800°F to 3600°F or centigrade equivalents. Pyro

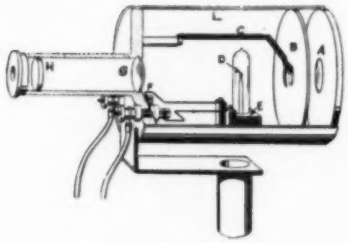
7. Radiation Pyrometers



Pyro-radiation pyrometer; self-contained unit for use in industrial plants. Two standards, double ranges: 1000°F to 2400°F to 3600°F. Pyro



Ardometer; indicating radiation pyrometer furnished in five ranges between 0°F and 3600°F. Water-cooled housing designed to protect instrument from excessive temperatures or sting-out. Bac

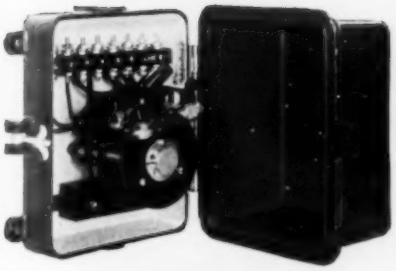


Radiation pyrometer for use with indicating or recording and controlling potentiometers. Upper temperature limit, 3300°F. Brown

Radiation-type vacuum tube; thermocouple elements are mounted in glass bulbs highly evacuated. Can be used with galvanometers, potentiometers, millivoltmeters, recorders and controllers. The instrument has high sensitivity and rapid response. GE

Radiation pyrometers; recording and indicating types; portable type. Ranges between 700°F and 5000°F. T-A

8. Automatic Control Equipment



The "Moto-Merco" relay is used with two-position pyrometers having sustained contacts and a differential between low and high contacts. Its function is to provide, in addition to the low and high contacts, a positive normal contact for use in controlling temperatures. Employs the telechron motor and mercury switches. Au

---

Series 2700 program timers are used for controlling the time-temperature cycles of furnaces. They are also used for switching of thermocouples and pyrometer circuits. Certain types are used for providing regular impulses for slow movement of pyrometer contact tables. Au

---

Recording and indicating pyrometer control, operating from thermocouples and resistance elements. May be used over large range of temperatures for any industrial use. Bris

---

Automatic control equipment available in air-operated and automatic types for many industrial uses. Brown

---

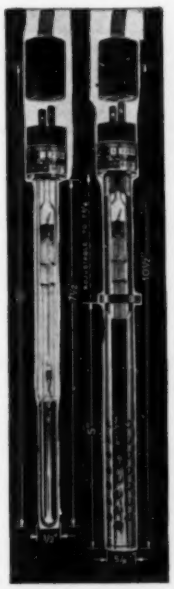
The Cenco-DeKhotinsky thermoregulators consist of a lead-coated, bimetallic helix; a head containing the adjusting mechanism; and a movable contact arm. Temperature settings from −45°C to 250°C may be made. The bimetallic element is sensitive to changes of between 0.2°C and 0.3°C. Cenco

Automatic control equipment which consists of a millivoltmeter or direct deflection instrument for control of temperatures within the pyrometer range up to 3000°F. May be used with relay and calibrated for any standard type of thermocouples. Eng

---

The Hagan bimetallic thermostat, used for temperature control in conjunction with steam reducing and desuperheating stations, temperature control of superheated steam in various types of boilers and separately fired superheaters, and temperature control of oil stills. Hagan

---



Red-top thermoregulators are adjustable mercury-in-glass thermostats. Available with or without armored jackets with settings from −30°F to 500°F. Relay should be used to avoid excess current. H-B

Alnor pyrometer controller for electric furnaces makes use of thermocouples and electronic amplifier. It is available in temperature ranges from 0–600°F to 0–3000°F or centigrade equivalent. Mercury switches are used to break currents up to 25 amperes. Ill

---

Johnson automatic controls making use of vapor pressure and liquid expansion, pressure spring equipment and bimetallic strips. Available in several ranges. John

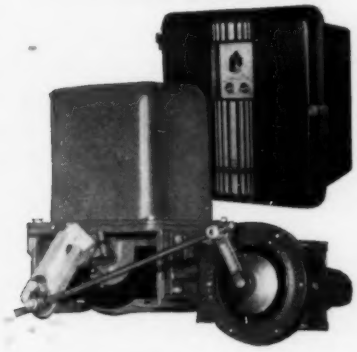
---

Precision switches making use of sensitive contact elements for thermostats actuated by rods, bimetal, bellows or wafers. May be used in automatic control equipment. Micro

---

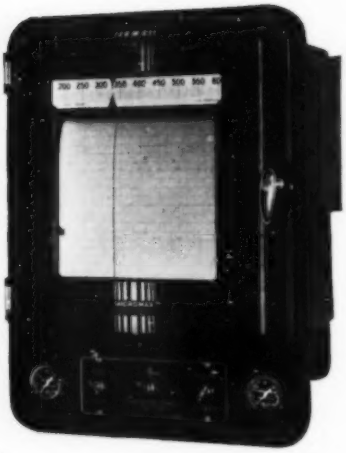
Acratherm and other controls for room temperature. Make use of bimetallic strip. Range 55°F to 85°F. Furnace controls with mercury switches for higher temperatures. Minn

---



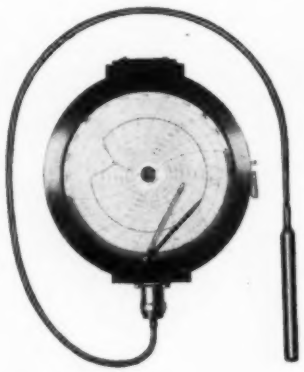
Micromax electric control; for extremely close temperature control by the regulation of an electrically-driven valve. Consists of three integral parts—a Micromax control instrument (Model S, R, or C), an M.E.C. control unit and a valve drive mechanism. Can be supplied factory-mounted on a steel panel, wired and tested, ready to connect to drive mechanism. L-N

Automatic Control Equipment (continued)



Micromax pneumatic control may be used where temperatures are to be controlled by the regulation of diaphragm valves. Employs two balances—an electrical balance for measurement, a pneumatic balance for control, linked by a stem-type pilot valve. L-N

Temperature controllers making use of vapor pressure, gas-filled or liquid expansion temperature indicators. Ranges between −100°F and 1100°F or centigrade equivalents. Both air-operated and indicating or recording types. M-N



Indicating and recording temperature controllers over various temperature ranges. Temperature indicator is of pressure spring type. Limit switches and other control devices are available. Part

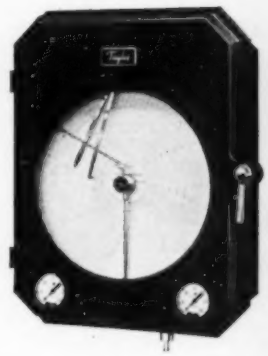
Merc-to-Merc thermoregulators consist of bulb containing mercury leading into two columns. When temperature rises, mercury in columns comes together, closing electrical contact. Range to 700°F. Smallest sensitivity 0.1°F. Phil

Powers automatic controls for room temperatures, water temperatures and industrial processes. Vapor pressure disk and spring used as actuating elements. Po

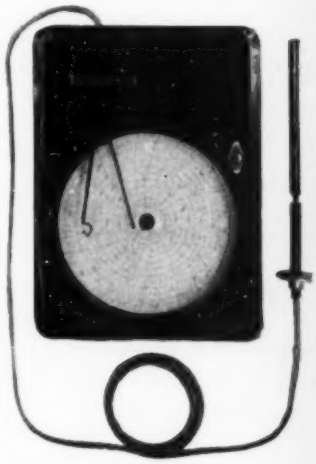
Measuring and controlling instruments making use of air-operated and motor-driven valves and accessories are manufactured. Panels and panel equipment available. Tag

Automatic control equipment; for use with oil, gas or electrically heated equipment. Furnished in conjunction with motor-operated valves. Applicable to automatic control actuated by thermocouples, resistance thermometer bulbs and expansion-type actuating device. T-A

United Cinephone Corporation announces that they are equipped to engineer and build electronic control apparatus actuated through the mediums of photoelectricity, thermocoupling, thermostats, or contacting thermometers. UCC



Fulscope controllers are useful for controlling temperature, pressure, rate of flow and liquid level in either recording or indicating models. Sensitivity may be adjusted. Tay



Therm-otrol is an indicating or recording thermometer plus Wheelco "no contact" control. The latter consists of small high frequency radio-oscillator connected to coils which automatically follow galvanometer. Available in several ranges to 100°F. Uses circular chart. Whe

9. Books on Heat and Temperature Measurement

Title	Author	No. of Pages	Date of Publication
	Cambridge University Press		
	Macmillan, 60 Fifth Avenue, New York, N. Y.		
Magnestism and Very Low Temperatures	H. B. G. Casimir	108 14 text figures	May, 1940
Low Temperature Physics	M. and B. Ruhemann	324 numerous text figures	1937
Combustion, Flames and Explosions of Gases	B. Lewis and G. von Elbe	432 79 text figures	1938
Statistical Thermodynamics	R. H. Fowler and E. A. Guggenheim	704	1939
	Chemical Publishing Co., Inc.		
	148 Lafayette Street, New York, N. Y.		
Pressure Gauges, Indicators, Thermometers, Pyrometers	James Smith	144	1939
Low Temperature Physics	L. C. Jackson	122	1934

Thermionic Emission	T. J. Jones	108	1936
Thermionic Phenomena	Eugene Bloch	145	1927
Ebulliometry	W. Swietoslawski	204	1937
Flame	de C. Ellis and W. A. Kirby	106	1936
Warming Buildings by Electricity	Frank C. Smith	168	1934
Hot Water Supply	F. W. Dye	255	1937
Steam Heating	F. W. Dye	212	1934
Heating and Air Conditioning of Buildings	O. Faber and J. R. Kell	434	1936
Industrial Furnace Technique	A. Hermansen	293	1929
The Technology of Low Temperature Carbonization	M. Gentry	399	1928
	Longmans, Green and Company		
	55 Fifth Avenue, New York, N. Y.		
A Text Book on Heat	A. W. Barton	286	1933
Heat	W. J. R. Calvert	344	1922
A Textbook of Thermodynamics	F. E. Hoare	319	1938 (second edition)
Intermediate Heat	R. A. Houstoun	121	1928
Tables and Diagrams of the Thermal Properties of Saturated and Superheated Steam	L. S. Marks and H. N. Davis	106	1909
An Introduction to Thermodynamics for Chemists	D. J. Martin	350	1933
Heat Engines	W. Ripper	337	1939 (new edition)
Steam Engine Theory and Practice	W. Ripper	853	1932 (eighth edition, revised by W. J. Goudie)
Treatise on Thermodynamics	M. Planck	309	1927 (third edition from seventh German edition)
Heat Engines	A. C. Walshaw	413	1938
	The Macmillan Company		
	60 Fifth Avenue, New York, N. Y.		
Combustion, Flames and Explosion of Gases	Lewis and Von Elbe	415	1938
Applied Thermodynamics	Faires	374	1938
Problems on Applied Thermodynamics	Faires and Brewer	140	1938
Elementary Thermodynamics	Faires	225	1938
Heat Engines	Cross	607	1930
Thermodynamics for Engineers	Ewing	389	1936
Heat for Advanced Students	Edser	487	1936
A Textbook of Heat	Allen and Maxwell	527	1939
	Prentice-Hall, Inc.		
	70 Fifth Avenue, New York, N. Y.		
Thermodynamics	Enrico Fermi	160	1937
Procedures in Experimental Physics	John Strong with the collaboration of H. Victor Neher, C. Hawley Cartwright, Albert E. Whitford, Roger Hayward	642	1938
	John Wiley and Sons, Inc.		
	440 Fourth Avenue, New York, N. Y.		
Heat	J. M. Cork,	279	1933
Thermodynamic Properties of Steam	J. H. Keenan and F. G. Keyes	89	1936
Textbook of Thermodynamics	P. S. Epstein	406	1937
Experimental Mechanical Engineering	H. D. Diederichs and W. C. Andrae	1082	1930
Mechanical Engineers' Handbook. Volume I. Power	R. T. Kent	1254	1936
Volume II. Design Shop Practice	R. T. Kent	1378	1938
Heat-Power Engineering. *Part I.* Thermodynamics and Prime Movers	W. N. Barnard and F. O. Ellenwood, Hirshfeld, C. F.	493	1926
Part II. Steam Generating Apparatus		871	1933
Part III. Auxiliary Equipment		419	1933

10. Code for Addresses of Manufacturers

Am	American Thermometer Company, St. Louis, Mo.
Au	Automatic Temperature Control Company, 34 East Logan St., Philadelphia, Pa.
Bac	Bacharach Industrial Instrument Co., 7000 Bennett St., Pittsburgh, Pa.
Bak	Baker and Company, Inc., 113 Astor St., Newark, N. J.
Bid	Biddle, James G., Co., 1211 Arch St., Philadelphia, Pa.
Bis	Bishop, J., and Co., Platinum Works, Malvern, Pa.
Bris	Bristol Co., Waterbury, Conn.
Bro	Brooklyn Thermometer Co., 246 Fifth Ave., New York, N. Y.
Brown	Brown Instrument Co., 4482 Wayne Ave., Philadelphia, Pa.
Bueh	Buehler, Adolph I., 228 North La Salle St. at Wacker Dr., Chicago, Ill.
Cenco	Central Scientific Co., 1700 W. Irving Park Road, Chicago, Ill.
Co	Cooper Oven Thermometer Co., Pequabuck, Conn.
Cor	Corning Glass Works, Corning, N. Y.
Dai	Daigger, A., and Co., 159 West Kinzie St., Chicago, Ill.
Def	Defender Automatic Regulator Company, St. Louis, Mo.
De	Denver Fire Clay Co., P.O. Box 5510, Denver, Colo.
Die	Dietert, Harry W., Co., 9330 Roselawn Ave., Detroit, Mich.
Dill	Dillon, W. C., 185 N. Wabash Ave, Chicago, Ill.
EKC	Eastman Kodak Co., Rochester, N. Y.
E-A	Eimer and Amend, Third Ave., 18th to 19th St., New York, N. Y.
Eis	Eisele and Co., 400 First Ave., N., Nashville, Tenn.
Eitz	Eitzen, Louis C., Co., 280 Broadway, New York, N. Y.
Eng	Engelhard, Charles, Inc., 90 Chestnut St., Newark, N. J.
Epp	Eppley Laboratory, Inc., Newport, R. I.
Fai	Faichney Instrument Corp., Watertown, N. Y.
Fee	Fee and Stemwedel, 4949 North Pulaski Road, Chicago, Ill.
Fish	Fisher Scientific Co., 711–723 Forbes St., Pittsburgh, Pa.
Flei	Fleischhauer, Fr., and Son, 8936 187th Place, Hollis, N. Y.
Fox	Foxboro Co., Neponset Ave., Foxboro, Mass.
Fri	Friez, Julien P., and Sons, Inc., Baltimore, Md.
Fu	Fuess, R., Inc., 39 W. 60 St., New York, N. Y.
GE	General Electric Co., 1 River Road, Schenectady, N. Y.
Gor	Gordon, Claud S., Co., 1524 South Western Ave., Chicago, Ill.
Gove	Gove's Sons, Hartley, Vineland, N. J.
Gre	Green, Henry J., 1191 Bedford Ave., Brooklyn, N. Y.
Grei	Greiner, Otto R., 55 Plane St., Newark, N. J.
Haak	Haak's Sons, Otto, 223 West Rockland St., Philadelphia, Pa.
H-B	H-B Instrument Co., 2518 North Broad St., Philadelphia, Pa.
Hagan	Hagan Corp., 600 Bowman Bldg., Pittsburgh, Pa.
Hill	Hill, E. Vernon, 6826 W. Highland Ave., Chicago, Ill.
Hos	Hoskins Manufacturing Co., Lawton Ave. and Buchanan St., Detroit, Mich.
Ill	Illinois Testing Laboratories, Inc., 420 La Salle St., Chicago, Ill.
John	Johnson Service Co., Milwaukee, Wis.
Kim	Kimble Glass Co., Vineland, N. J.
L-N	Leeds and Northrup Co., 4901 Stenton Ave., Phiadelphia, Pa.
MMM	Manning, Maxwell and Moore, Inc., Bridgeport, Conn.
Mar	Marsh, Jas. P., Corp., 2063 Southport Ave., Chicago, Ill.

Code for Addresses of Manufacturers (continued)

Marsh	Marshall, L. H., Co., 2525 N. High St., Columbus, Ohio
M-N	Mason-Neilan Regulator Co., 1190 Adams St., Boston, Mass.
Micro	Micro Switch Corp., 15 East Spring St., Freeport, Ill.
Minn	Minneapolis-Honeywell Regulator Co., Minneapolis, Minn.
Moe	Moeller Instrument Co., 132nd St. and 89th Ave., Richmond Hill, N.Y.
Moto	Moto Meter Gauge and Equipment Division of The Electric Auto-Lite Co., Chrysler Bldg., New York, N. Y.
Nu	Nurnberg Thermometer Co., Inc., 397 Bridge St., Brooklyn, N. Y.
Pal	Palmer Co., 2511 Norwood Ave., Cincinnati, Norwood, Ohio
Palo	Palo-Myers Inc., 81 Reade St., New York, N. Y.
Parr	Parr Instrument Co., Moline, Ill.
Part	Partlow Corp., Campion Road and Partlow St., New Hartford, N. Y.
Pec	Pecorella Manufacturing Co., 64 Stanhope St., Brooklyn, N. Y.
Phil	Philadelphia Thermometer Co. 915 Filbert St., Philadelphia, Pa.
Po	Powers Regulator Co., 2720 Greenview Ave., Chicago, Ill.
Prac	Practical Instrument Co., 2717 N. Ashland, Chicago, Ill.
Pre	Precision Thermometer and Instrument Co., 1434 Brandywine St., Philadelphia, Pa.
Pyro	Pyrometer Instrument Co., 103-107 Lafayette St., New York, N. Y.
Raws	Rawson Electrical Instrument Co., Cambridge, Mass.
Repu	Republic Flow Meters Co., 2240 Diversey Parkway, Chicago, Ill.
Rich	Richards, Arklay S., Co., 26 Parker St., Newton Centre, Mass.
Roc	Rochester Manufacturing Co., Inc., Rochester, N. Y.
Roll	Roller-Smith Co., 2132 Woolworth Bldg., New York, N. Y.
Rub	Rubicon Co., 29 North Sixth St., Philadelphia, Pa.
Ryan	Ryan Recording Thermometer Co., 654 Mill St., Los Angeles, Calif.
Schu	Schultheis, E. W., Corp., 812-814 Wyckoff Ave., Brooklyn, N. Y.
Sci	Scientific Glass Apparatus Co., 49 Ackerman St., Bloomfield, N. J.
Stan	Standard Thermometer, Inc., 65 Shirley St., Boston, Mass.
Tag	Tagliabue Manufacturing Co., Park and Nostrand Ave., Brooklyn, N. Y.
Tam	Tamms Silica Co., 228 N. LaSalle St., Chicago, Ill.
Tay	Taylor Instrument Co., 95 Ames St., Rochester, N. Y.
Tes	Testrite Instrument Co., 57 East 11th St., New York, N. Y.
Ther	Thermometer Supply Co., 64 Fulton St., New York, N. Y.
Trer	Trerice, H. O., Co., 1420 Lafayette Blvd. West, Detroit, Mich.
T-A	Thwing-Albert Instrument Co., 3323 Lancaster Ave., Philadelphia, Pa.
UCC	United Cinephone Corp., Torrington, Conn.
USG	United States Gauge Co., 44 Beaver St., New York, N. Y.
Wek	Weksler Thermometer Corp., 535 Pearl St., New York, N. Y.
Wel	Welch, W. M., Manufacturing Co., 1515 Sedgwick St., Chicago, Ill.
Wes	Weston Electrical Instrument Corp., 614 Frelinghuysen Ave., Newark, N. J.
Whe	Wheelco Instruments Co., 1933 South Halsted St., Chicago, Ill

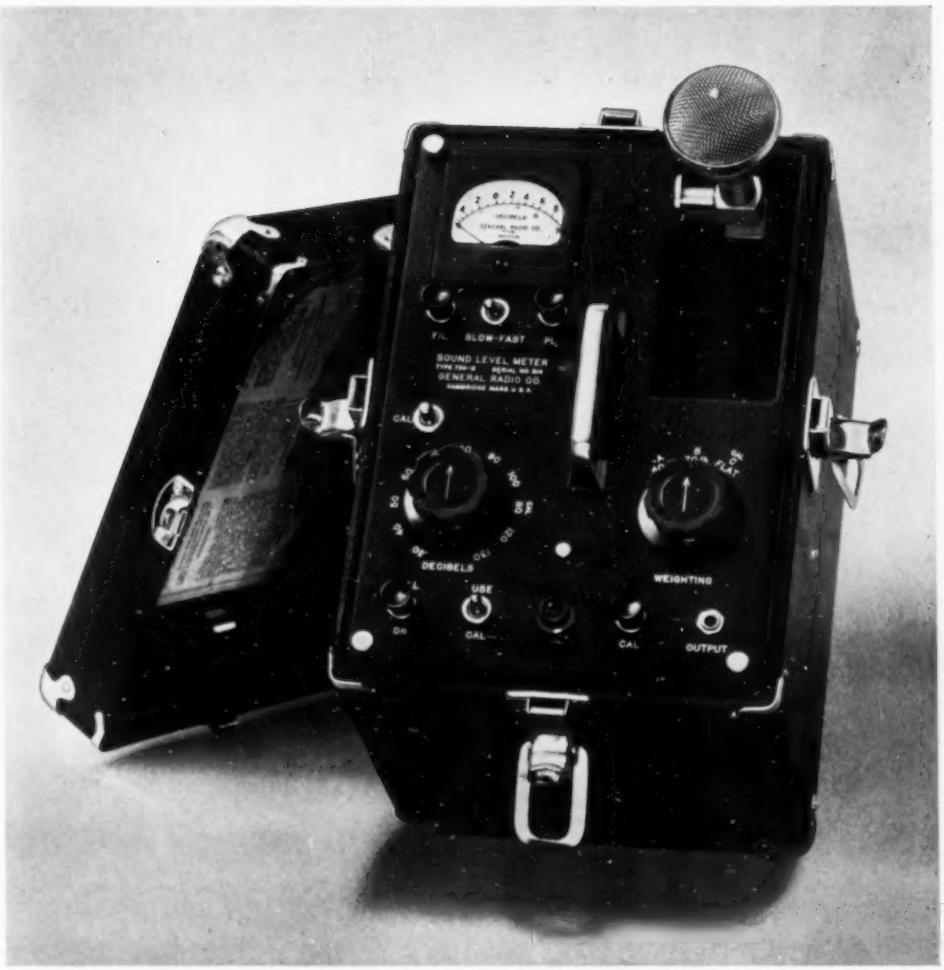
INDEX TO ADVERTISERS

Name	*Page*
American Instrument Company — Ion Type X-Ray Tube. Powder Spectrum Diffraction Cameras. Scientific Instruments and Supplies.	xiii
Baker & Company, Inc. — Platinum crucibles, dishes, triangles, filter cones, anodes, cathodes, electrodes, platinum tipped crucible tongs, fine wires and bismuth foil.	xv
Bausch & Lomb Optical Company — Makers of Microscopes, Microtomes, Colorimeters, Refractometers, Spectrometers, Balopticons, Photomicrographic and Microprojection Apparatus and related instruments. Also makers of Orthogon Eyeglass Lenses for Better Vision.	iii
James G. Biddle Company — "Jagabi" Rheostats; Adam Hilger and Kipp & Zonen Optical Instruments; "Pointolite" Lamps; Electrical Testing and Speed-measuring Instruments.	xv
Central Scientific Company — Manufacturers of Cenco Physical Apparatus and Instruments to meet all requirements of University, College and High School Physics Laboratories. Specializing in high vacuum pumps and development of instruments and apparatus for various sciences.	Cover 4
Clifford Mfg. Company — Hydron metallic bellows for temperature and pressure control devices. Data for engineers.	xiii
Eastman Kodak Company — Purified Organic Chemicals for research purposes; Plates for Photography, Photomicrography, Spectroscopy, Photometry, Astronomy; Wratten Light Filters; Cameras and Films.	vii
The Eppley Laboratory, Inc. — Standard Cells, thermopiles, pyrheliometers and temperature bridges.	vii
Gaertner Scientific Corporation — Spectroscopes, Spectrometers, Spectrographs, Spectrophotometers, Heliostats, Measuring Microscopes, Comparators, Cathetometers, Reading Telescopes, Interferometers, Chronographs, Dividing Machines, etc.	ix
General Radio Company — Manufacturers of electronic measuring instruments; vacuum-tube voltmeters, amplifiers and oscillators; wave analyzers, noise meters and analyzers, stroboscopes; laboratory standards of capacitance, inductance and frequency; impedance bridges, decade resistors and condensers; air condensers and variable inductors; rheostats, Variacs, transformers; other laboratory accessories.	Cover 3
International Resistance Company — Manufacturers of metallized and wirewound fixed and variable Resistors including high voltage and high frequency types.	xi
Leeds & Northrup Company — Manufacturers of Galvanometers, Resistors, Bridges, Condensers, Inductances, Potentiometers, Testing Sets; Temperature Measuring, Recording and Controlling Apparatus; Instruments for Measuring and Controlling Conductivity of Electrolytes and Hydrogen Ion Concentrations.	i
The Linde Air Products Co. — Oxygen, Argon, Helium, Krypton, Neon, Xenon, Rare Gas Mixtures, Nitrogen, Hydrogen, Calcium Carbide, Acetylene, equipment for Oxy-Acetylene welding and cutting.	xi
McGraw-Hill Book Company, Inc.	ix
Mountain States Publishing Company	xv
Rubicon Company — Galvanometers, electrometers, potentiometers, Wheatstone and Kelvin bridges, resistance boxes, hydrogen ion and conductivity apparatus.	xiii
Shallcross Mfg. Company — Taylor High Voltage Resistors for Voltmeter Multipliers. High resistance and high Wattage Decade Boxes and other laboratory instruments. Super Akra Ohm wire wound, non-inductive and accurate resistors. Special resistors for special purposes.	xv
The Society of Exploration Geophysicists	xi
Spencer Lens Company — Microscopes, Microtomes, projection equipment, Spectrometers, Colorimeters, complete line of optical instruments.	xiii
Westinghouse Electric & Manufacturing Company	v
John Wiley & Sons, Inc.	ii

Want to Purchase

Good used Petrographer's Polarizing Microscope and accessories. Give full description to American Lava Corporation, Chattanooga, Tenn.

New Sound-Level Meter



Greater Accuracy • Simplified Operation • Higher Stability

BASED on the experience of hundreds of users of the original Type 759-A Sound-Level Meter over the past three years and with considerable development by our engineers, General Radio announces a new model Sound-Level Meter. The new instrument has many electrical improvements which add considerably to its usefulness in laboratory and industrial sound-measurement fields.

FEATURES:

NEW MICROPHONE—development of special type with greater sensitivity—increased ruggedness and improved design substantially unaffected by ordinary variations in temperature and humidity

SLOW-FAST METER—two-speed meter—control switch selects either—fast position, meter movement corresponds to A.S.A. specifications—slow position, movement heavily damped to smooth out temporary transients for measuring average level of fluctuations

INCREASED SENSITIVITY RANGE—now increased to a maximum of +140 db

SIMPLIFIED CONTROLS—complete decibel range covered by a single control knob

NEW CIRCUIT—greatly simplified to increase stability—double output stage one-half operating the indicating meter and other half connected to an output jack for use with an analyzer, external meter or telephones—meter readings entirely independent of load connected to "output" jack

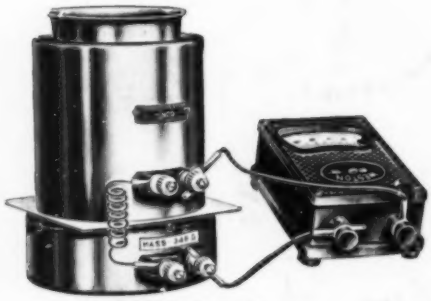
NO INCREASE IN PRICE—price remains at $195.00 complete with batteries for immediate operation

• Write for Bulletin 589

GENERAL RADIO COMPANY, Cambridge, Massachusetts

CENCO-FITCH
HEAT CONDUCTIVITY APPARATUS

For Selection of Heat Insulating Materials
From Measurements of Thermal Conductivity



77555 shown in use

Accurate Values

Simple Technique

Quick Results

THE Cenco-Fitch Heat Conductivity Apparatus consists of a metal receiving block of known thermal capacity within which a thermocouple is embedded near the upper surface, and an insulated heat source vessel with bottom of thick machined copper which also contains an embedded thermocouple. When electrical connections have been made, the material to be tested is placed beneath the heat source vessel, which is filled with boiling water, and allowed to stand until the galvanometer deflection has become steady. At this point the test piece and heat source are placed upon the receiving block. Galvanometer readings are then made at equal time intervals, which when plotted upon semilogarithmic paper give a straight line, the slope of which is a function of the thermal conductivity and the constants of the apparatus. The thermal conductivity of poorly conducting materials up to 10 mm. thick is measured quickly and accurately. Instructions for use are provided with each apparatus.

77555.	**Cenco-Fitch Heat Conductivity Apparatus**	**$20.00**
16550A.	**Cenco Immersion Heater, 500 watts, 115 volts**	**5.00**
16580.	**Connecting Cord with plug for No. 16550A Heater**	**.75**
82615C.	**Galvanometer, Weston, for use with No. 77555 Conductivity Apparatus**	**30.00**
88115.	**Semi-Logarithmic Paper. Package of 100 sheets**	**1.75**

CENTRAL SCIENTIFIC COMPANY

SCIENTIFIC INSTRUMENTS — TRADE MARK CENCO REG. U.S. PAT. OFF. — LABORATORY APPARATUS

New York • Boston • CHICAGO • Toronto • San Francisco

LANCASTER PRESS, INC., LANCASTER, PA.